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High-Temperature, High-Pressure Particulate Control with Ceramic Bag Filters

Acurex Corp, Mountain View, CA

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, NC

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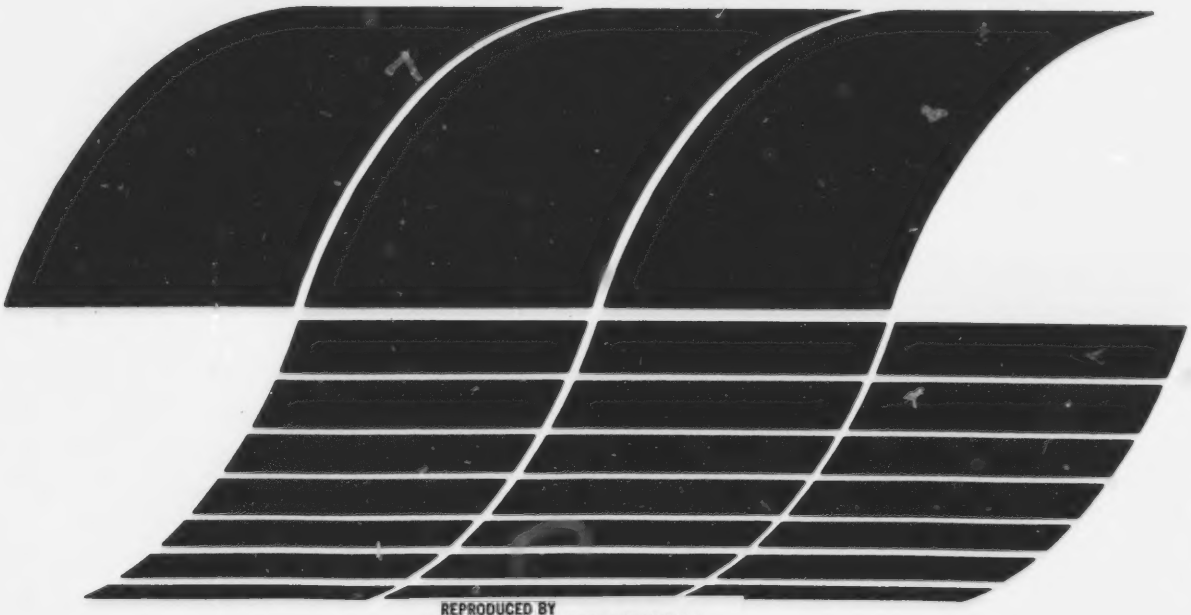

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October 1978

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SECTION 1

INTRODUCTION

Many advanced technology processes currently being developed require removing particles from high temperature and pressure gas streams. An objective of developing these processes is to increase coal use by making it economically efficient and environmentally safe. The processes most actively being studied are pressurized fluidized bed combustion (PFBC) and gasification combined cycle (GCC) plants. These processes involve expanding the high temperature and pressure gases across a turbine which generates power to produce electricity. Such applications require removing particle flyash from the gas streams before it expands across the turbine.

In the PFBC, coal is burned in a fluidized bed of limestone (which removes the SO_2), and heat is transferred to tubes in the fluidized bed. Up to 80 percent of the recoverable heat value of the coal is removed in the fluidized bed, and the gas exits at 815^{o}C (1500^{o}F) and 10 atm pressure.

The gas must then be expanded through a gas turbine to recover the remaining energy. However, previous investigations showed that large particles erode turbine blades, and small particles cause deposits that choke the turbine. To protect the turbine, some high temperature particulate control is required. Moreover, since it would not be

economical to duplicate particulate control for environmental regulations, following the turbine, high temperature particle control must also meet new source performance environmental standards for coal-fired utilities. This currently allows emissions to be not greater the 0.1 lb million Btu ($0.043 g/M^J$) and may be reduced.

To meet both the environmental and turbine requirements, a system consisting of two cyclones and a filter was studied. Although the two cyclones lower the overall particle concentrations, they fail to remove small particles. Concentrations leaving the second cyclone can be as high as 2.29 g/Nm^3 (1.0 gr/scf) and have a mass median diameter of 5.0 μm. Under the contract, research was aimed at demonstrating the feasibility of using ceramic filters in a barrier filter system to accomplish the tertiary collection of fine particles following a cyclone train.

Major goals of this program were to:

- Design and build a filter media test facility capable of operating at 815°C and 10 atm pressure
- Test available ceramic fiber forms (woven cloths, felted mats) to determine if any can survive mechanical displacements, and accelerations that are likely to be encountered in online cleaning of high temperature filter applications
- Develop preliminary performance data for those configurations which appear most promising for high temperature filter applications
- Make recommendations based on the experience and data collected

Conclusions

Research on bench-scale indicates that fine particle control at high temperature and pressure can be achieved using barrier filtration by

ceramic filter beds. Evidence in support of this contention includes the following:

- A theoretical basis exists for it
- Several of the ceramic paper and felt materials are capable of removing fine particles at high efficiency without excessive filter weights
- The ceramic paper and felt materials have filtration characteristics and performed similarly to paper and felt commercial filter media in a series of filter media tests
- The ceramic woven materials in general were characterized by large pores and poor collection efficiency in the dust loading tests. The range of parameters exhibited by the various materials, however, indicates that an acceptable woven ceramic filter media can probably be fabricated; but such filter media would have the same limitations as currently available woven filters. That is, acceptable performance would only occur at low air-to-cloth ratios.
- "Blanket" ceramic fiber materials (felts) consisting of small diameter fibers (3.0 μm) appear to be the most promising materials for high temperature and pressure applications because of their combination of good filtration performance and relatively high strength
- Accelerated media cleaning tests at high temperatures and pressures show that several ceramic filter structures are capable of surviving in excess of 50,000 cleaning pulses while maintaining pressure drop at acceptable levels

- Filtration tests at high temperature and pressure have shown that pressure drop can be controlled at air-to-cloth ratios of up to 9 cm/sec for a period more than 200 hours. Furthermore, this was accomplished while maintaining high efficiency particle removal with outlet concentrations less than published turbine requirements. The ability of the filter to control dust in high concentrations (14.4 g/Nm^3) was also demonstrated.
- Theory as well as tests indicate that high filter media face velocity (air-to-cloth ratio) operation will be possible for a HTHP filter system. To accomplish operation at high air-to-cloth ratios will require special cleaning techniques. High filter velocity operation is a desirable objective because smaller, less expensive particle control equipment will result.
- Innovative cleaning and media support techniques can be designed which are compatible with the unique properties of ceramic filter media

Recommendations

Work performed under the contract represents a major advance in the state-of-the-art of filtration. High efficiency particle control can potentially be extended by over 500°C from current industrial limitations of 300°C. Consequently, Acurex strongly recommends that the government continue to support advanced development of ceramic fiber filtration technology to make the potential benefits arising from this development available to the public.

High temperature ceramic fiber filtration is not limited to applications for pressurized fluidized bed combustion but could provide

fine particle control in many high temperature industrial processes. Applications such as these could provide heat recovery after particle removal, offering substantial savings in energy.

Current trends in the development of pressurized fluidized bed (PFBC) combustion technology indicate there is a continuing hope that turbines can be adequately protected with particle removal from staged inertial separation devices. Military experience does not support this hope. Helicoptor turbine engines have been fitted with small high efficiency 2.5 cm diameter cyclone tube banks to extend service life from unacceptable to moderately acceptable in this application where dust loading is intermittent. The U.S. Army XM-1 Main Battle Tank is turbine powered. It employs a barrier filter system with a cyclone tube bank precleaner capable of providing engine intake air as clean as that required of heavy duty diesel engines. In the world's most severe dust conditions (YUMA proving ground Yuma, Arizona) dust loadings at the rear deck of a tracked vehicle are about 17 g/Nm^3. Dust loadings in excess of this are encountered in the exhaust of the PFBC.

To avoid a crash development program which would potentially delay the availability of advanced coal combustion systems, development of ceramic fiber, barrier filter systems should be continued. This development should proceed in parallel with current testing of inertial separators for PFBC applications. In the unlikely event that commerical power turbines will be shown capable of extended operation protected only by cyclones, the ceramic filter technology will still offer substantial benefits in other applications for protecting the environment.

A recommended development program should contain the following features:

Continued Laboratory-Scale Component Development

Many refinements are needed. Media configurations and ceramic screens should be tested to eliminate metal screens used to support the media in the current tests. Media cleaning techniques should be optimized. Further extension of filter velocity should be studied to provide data needed for economic predictions of commercial size equipment.

Pilot-Scale Tests

Pilot-scale units for PFBC applications should be built and tested (using current knowledge) to obtain field data needed for optimal designs.

Atmospheric Pressure Applications

Small-scale units should be built to investigate suitability for applications such as in the carbon black industry, at smelters and kilns and other high energy loss sites.

1.1 TEST PLAN

To provide the data needed to justify further development of high temperature, high pressure barrier filtration equipment, Acurex outlined the following test plan.

Obtain and Classify Ceramic Media Candidates

A survey of available ceramic filters and materials was made (a description of various media characteristics is included in Appendix A). The usable materials are generally made for insulation applications; those that are are not rigid in structure can be categorized into three groups: (1) Woven fabrics, produced by several companies, are made from yarns produced from a continuous length of ceramic fibers. Available in various weaves, they are flexible, and exhibit good strength relative to other ceramic fibrous structures. (2) Ceramic papers, constructed from short fibers generally held together with binders, are available and are

characterized by a relatively higher packing density of fibers and poor mechanical strength as compared with other ceramic fibrous structures. (3) Ceramic felts, consisting of relatively long fibers, are also available. They are relatively porous mats held together by randomly intermixing the fibers. They are flexible, and exhibit the highest strength in a filtration application.

Room Ambient Filter Media Tests

Over 30 ceramic media candidates were subjected to a series of filtration tests to determine their ability to remove particles from a gas stream. These basic filtration tests included Dioctylphtalate (DOP) smoke penetration tests, maximum pore size, permeability and flat sheet dust loading tests. Such tests were intended to show whether or not the media were capable of particle removal.

Mechanical Screening Tests

In this phase of the test program, the various candidate filter media were subjected to "filter cleaning loads" to determine their relative strength. These tests were performed on samples shaped into tubular bags. The tests were performed at an air-to-cloth ratio of 5 to 1 (2.54 cm/sec) at high temperatures and pressures in the presence of flyash. Samples were initially subjected to reverse flow cleaning cycles, but the primary test was pulse cycling. While maintaining forward flow, the sample was deflected with an air injected pulse using 5 to 10 pulses per minute from a reservoir pressure of 1100 kPa (160 psig), lasting 100 ms. The relative strength of each sample is determined by the number of cycles it withstands. If several thousand cycles are required for failure, then it is probable that the filter would last a long time if the cleaning technique is perfected.

Filtration Performance Tests

Those ceramic filter media identified from earlier tests as being most promising for the PFBC application were subjected to these tests, lasting 200 hours. Flyash was metered into the gas stream at a controlled rate while monitoring pressure drop. Pressure drop was controlled with cleaning cycles and overall dust removal efficiency was determined from analysis of the weight of dust fed and that which penetrated the test filter.

Ceramic Media Test Facility

The Hot Filtration Testing Facility (shown in Figure 1) is capable of subjecting 46 cm (18 inch) by 9.5 cm (3-3/4 inch) diameter test filters to an 815^{o}C, 10-atmosphere environment with air-to-cloth ratios from 0.5 to 5 cm/sec (1 to 10 ft/min). Moreover at reduced pressure (7 atm), higher face velocities are achievable, 9 cm/sec (18 ft/min). During high dust loadings, filter elements tested in the facility can be either reverse-flow or pulse-jet cleaned. There are three test chambers so that three bags can be tested simultaneously, though only one chamber was used.

The filter media test chamber (Figure 2) is a 244 cm (8 foot) by 30.4 cm (1 foot) diameter length of pipe with inlet and outlet tubes welded into the blind flanges on the top and bottom. The inside of the chamber is lined with 5 cm (2 inches) of castable refractory which surrounds a 10 kilowatt, 230 volt electrical resistance heater used to compensate for refractory and external piping heat losses. Clean, high temperature, high pressure air enters the chamber through the bottom. A separate line delivers dust from the feeder to the test chamber above the air inlet (Figure 2).

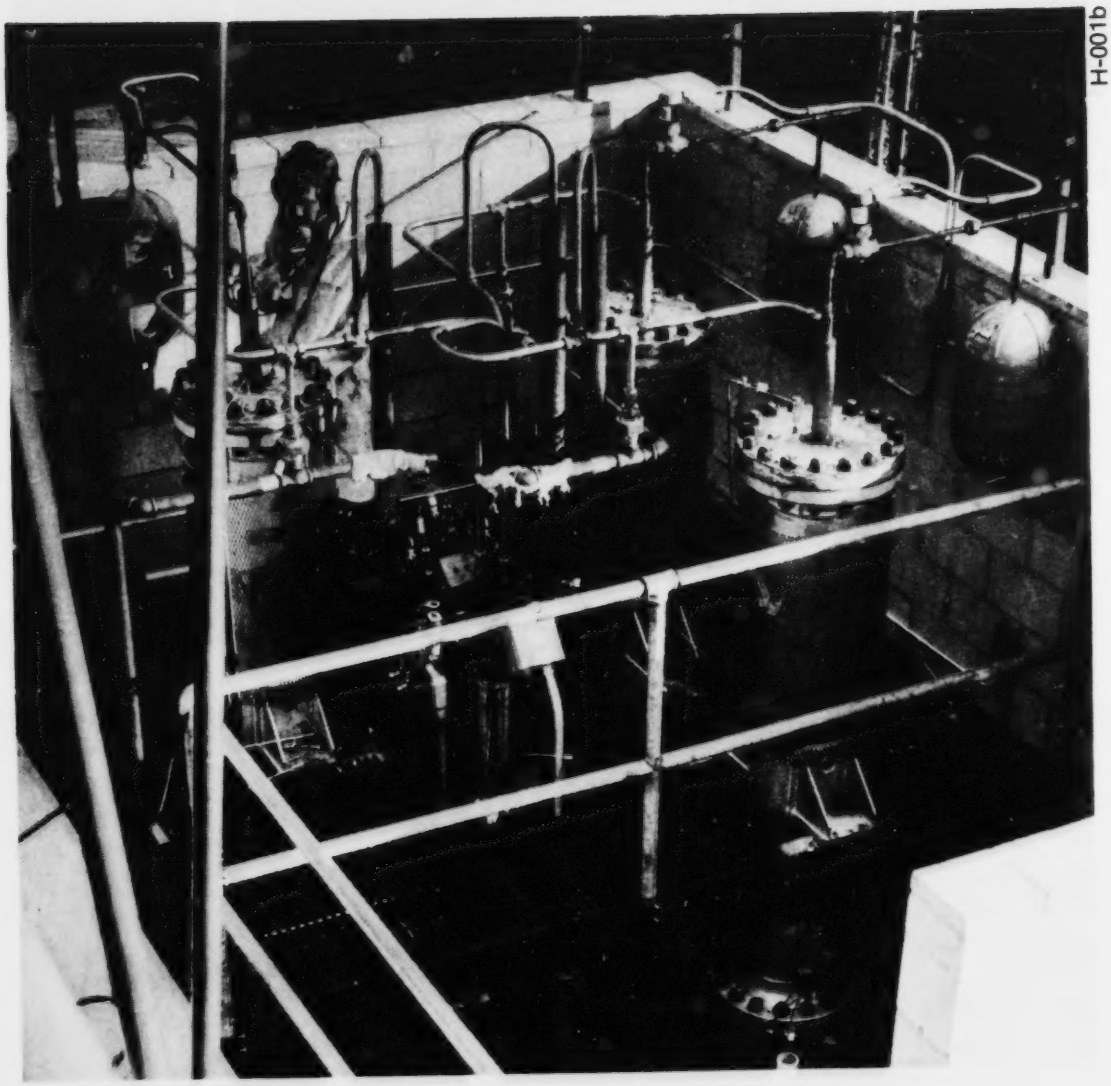

Figure 1. Hot filtration facility.

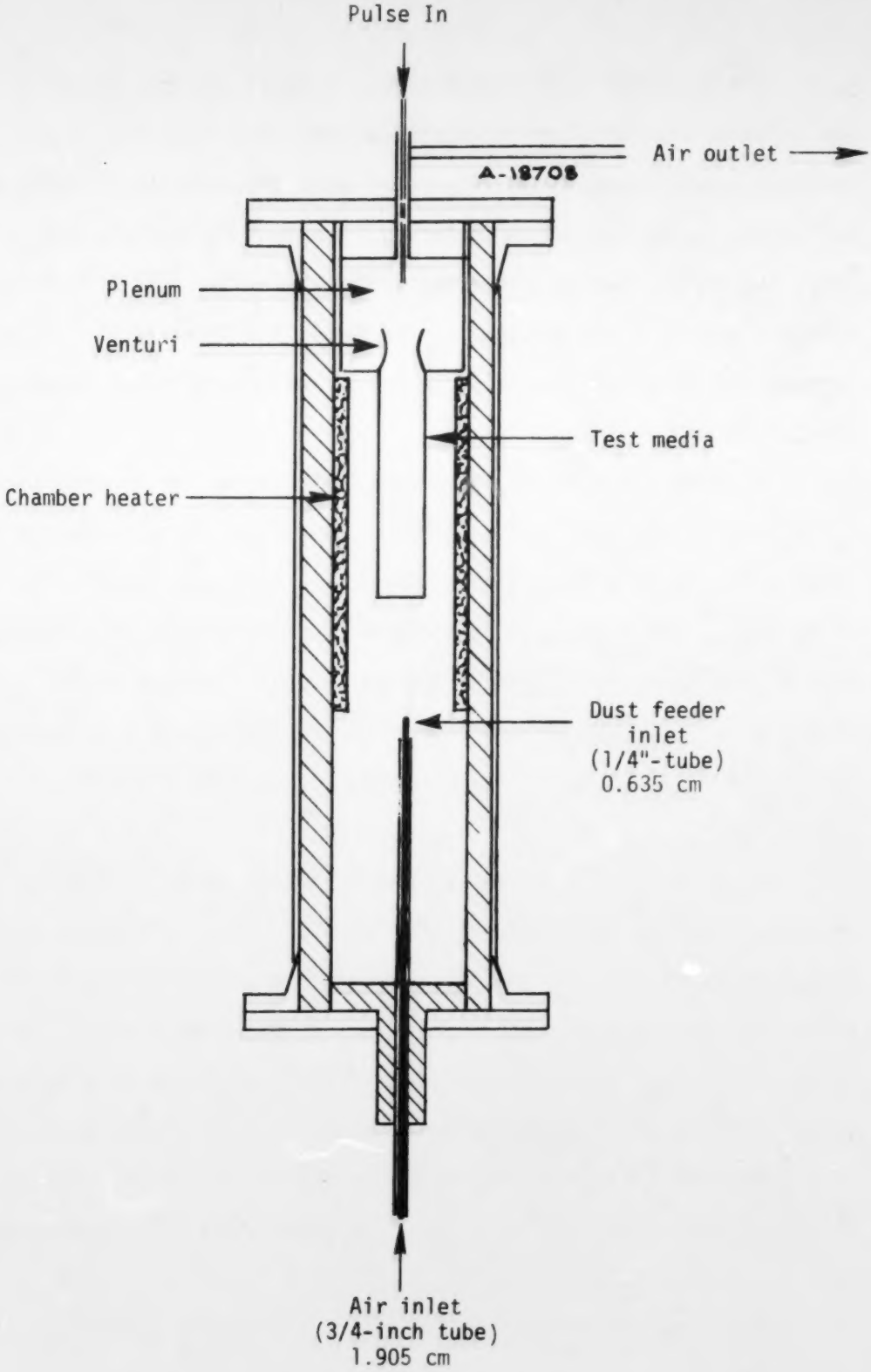

Figure 2. Test chamber cross section

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The 46 cm (18 inch) long test bag is above the dust feeder inlet. The cylinder shaped filter is mounted around a 9.2 cm (3-5/8 inch) diameter support cage screen (Figure 3) which prevents the filter from collapsing during outside-in filtering. The test filters are open at both ends, requiring clamping at the top around the venturi and at the bottom around a sealing plate attached to the cage. The filtered air passes through the venturi, into the pulse-jet plenum and exits the chamber through the outlet tube.

Once the filtered air leaves the test chamber, it is cooled with a forced air, finned tube heat exchanger. It is then directed through a commercial, low temperature, high efficiency, tube-type filter (Figure 4). This filter can be inspected periodically to determine the test filters particle removal efficiency. Downstream of the low temperature filter, the high-pressure air is bled through a sonic-flow metering orifice, through a noise suppressor, and vented to the atmosphere.

Gas temperatures are measured using thermocouples located at selected points within the facility (Figure 5). The air temperature measurements are taken at the test chamber inlet, above and below the test filter, at the low temperature filter, and at the orifice meter. These temperatures are displayed in the control room and stored on a 24 channel strip chart recorder. Pressure measurements using diaphragm pressure transducers are taken above and below the filter, at the orifice and in the pulse-jet reservoir (Figure 5). This information is also displayed and recorded in the control room.

There are two methods available for cleaning the test filter during operation: pulse-jet and reverse-flow. The pulse-jet method cleans the

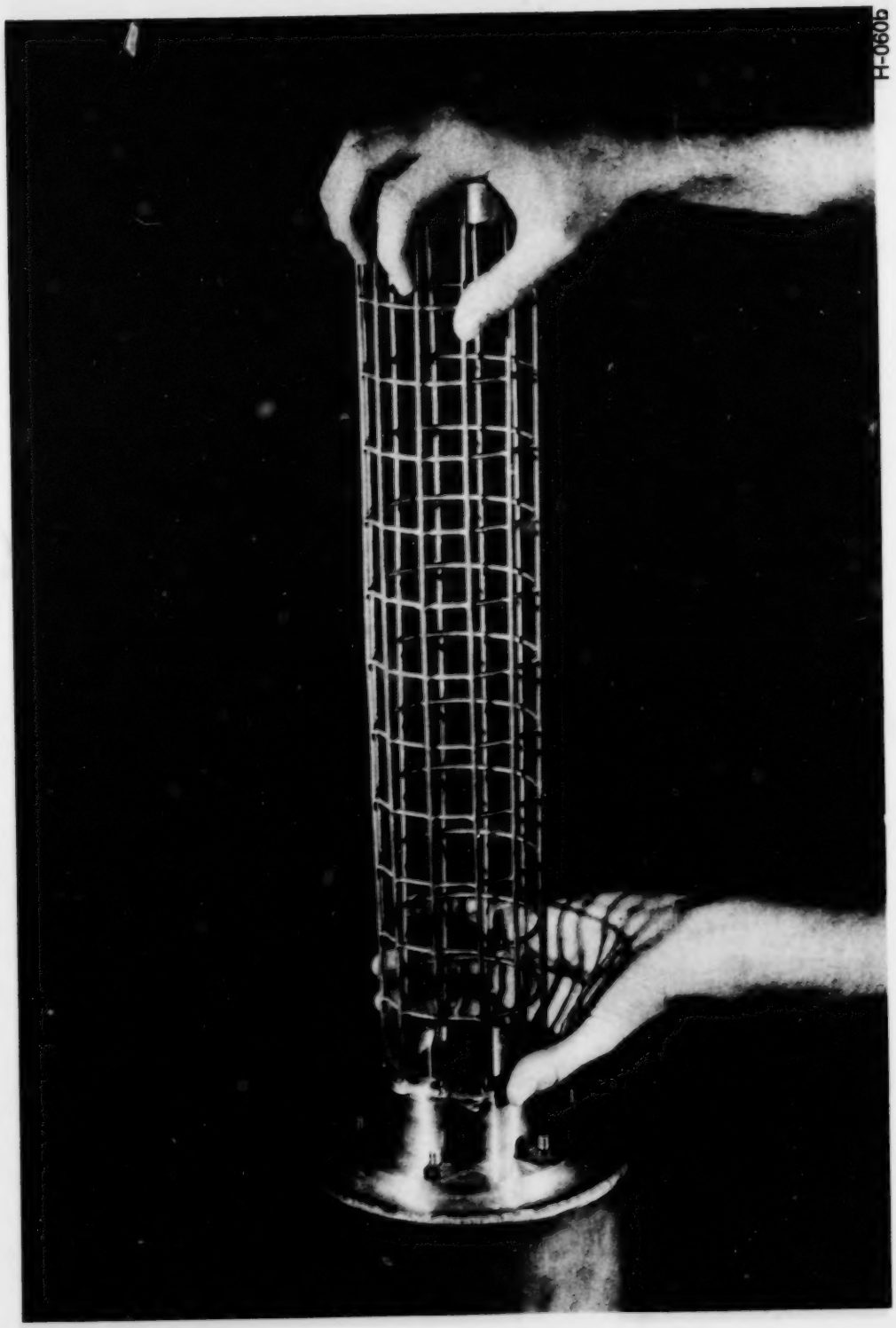

Figure 3. Filter support

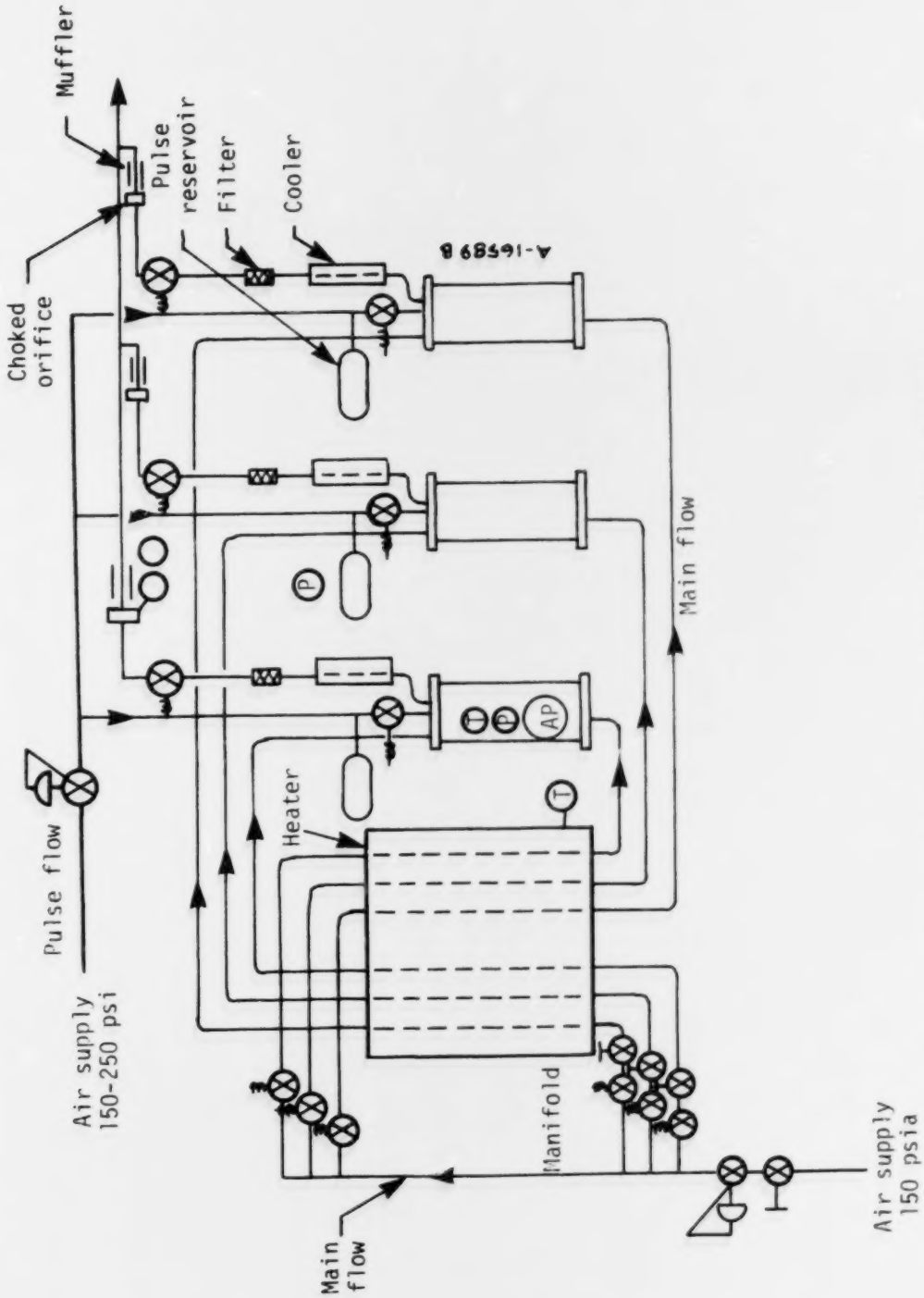

Figure 4. HTHP media test facility schematic.

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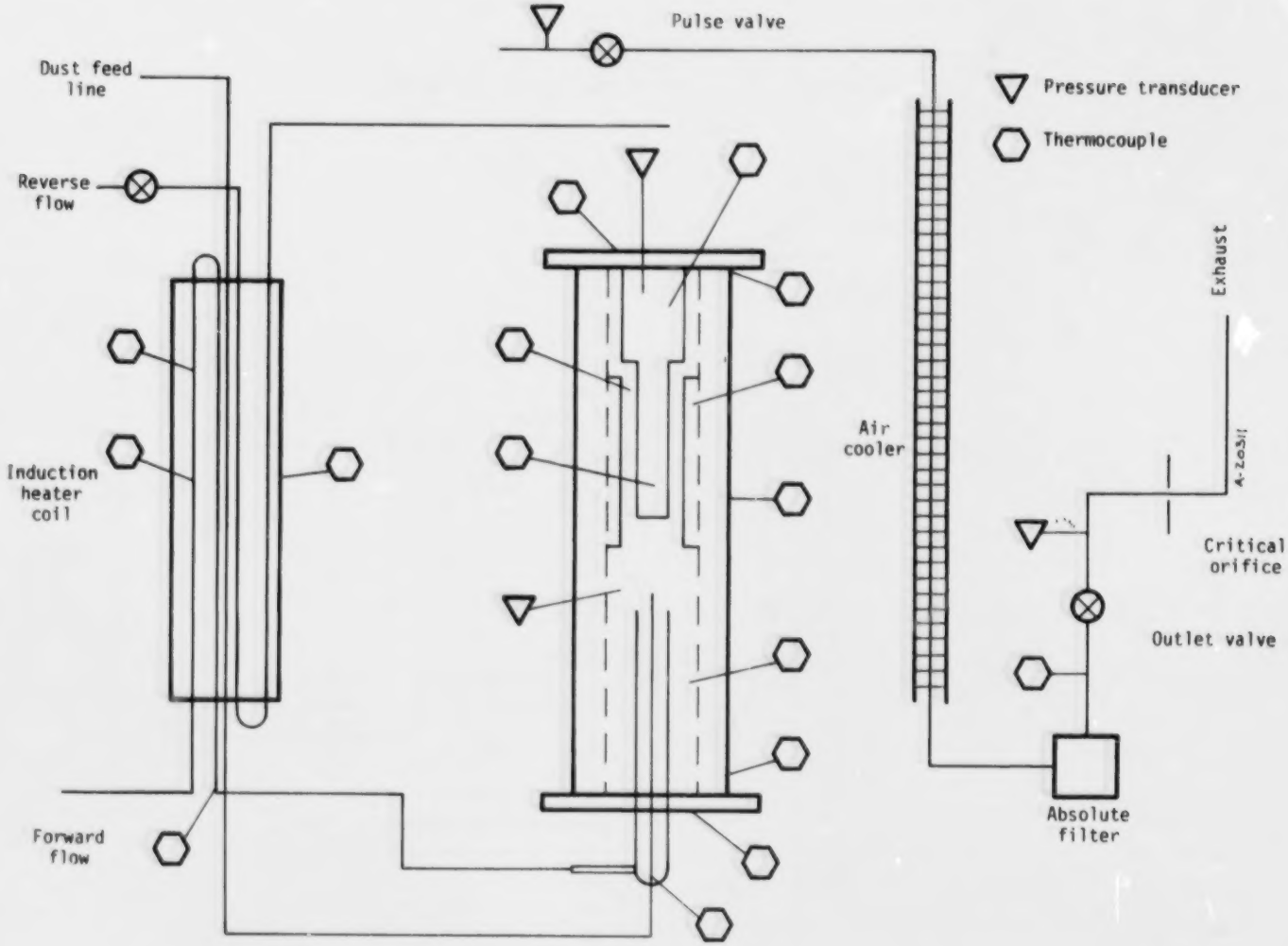

Figure 5. Test points, temperature/pressure.

filter using quick blasts of high pressure air, introduced at the clean side. Pulse pressure can be regulated from the test chamber pressure up to 1723 kPa (250 psi). Fast-acting solenoid valves provide 150 msec, or other duration, pulses at a variable interval. Pulse-jet cleaning can be done on line or off line.

Reverse-flow cleaning is a milder cleaning technique, requiring interrupting forward flow. The first step of the reverse-flow cleaning sequence is to shut off the main flow and bleed the test chamber down to a lower pressure. Next, the downstream outlet valve is shut and the main flow redirected in through the outlet tubes at the top of the chamber. The inside out flow across the filter blows the dust off the bag. This process stops when the chamber is once again pressurized. Reverse-flow effectiveness can be varied by adjusting either the bleed-down pressure or the rate of repressurization.

Both cleaning operations can be controlled manually or automatically at the control room. A digital time sequencer, in combination with a solid-state logic sequencer, can be programmed to provide automatic cleaning. The following parameters are adjustable: pulse frequency and duration, or reverse-flow frequency, bleed-down duration, and repressurization rate. The number of cleaning cycles in a given time can be either predetermined, or dependent on the pressure drop buildup across the bag.

Before entering the test chamber, the high-pressure air is heated to 815^{o}C (1500^{o}F). This is accomplished by passing the air through two 0.95 cm (3/8 inch) 310 stainless steel pipes 1.524 m (5 feet) long with a 20.3 cm (8 inch) long, 180^{o} turnaround so that the air has

approximately 3.55 m (11 feet) of travel while being heated in excess of 925°C by a 50 kW induction coil and power supply operating at 30 kHz.

In addition, a revolving disk, high-pressure dust feeder is used to introduce regulated amounts of flyash to the filter test chamber. It is enclosed in a separate pressurized vessel maintained at a pressure higher than the test chamber pressure.

Dust is metered from a dust hopper by filling a small groove in the rotating disk. The pressurized air enters the vessel below the disk and exits, carrying the dust out through a small tube directly above the dust filled grove. The feedrate is adjustable by varying either the disk rotation speed or the groove cross sectional area.

Primary Air Supply

The basic gas supply is by means of a 16.9 m^3/min (600 scfm) air compressor and receiver tank located adjacent to the existing facility block wall. The gas supply schematic is shown in Figure 4. The gas receiver tank provides a metered flow of compressed air to the main forward and reverse flow valves. The flow arrangement is unique in that it uses a pipe cluster inside the induction coil to heat both its forward and reverse flow gas supply. Flow from the test chambers is routed through a finned heat exchanger and then into an absolute filter for efficiency data. Flowrates are determined by passing the gas through a choked orifice downstream of the absolute filter.

Secondary Air

Secondary air for the pulse-jet cleaning mode and operation of the dust feeder is from a smaller 2.1 m^3/min (75 cfm) compressor and receiver tank located behind the facility pit.

Cooling Water

Water from a cooling tower is piped to the inlet gas manifolds and through the induction coil and power supply for cooling purposes. It uses a recycling system for water conservation.

Chamber Heaters

In addition to the induction heater previously mentioned, the test chamber is heated by a chrome-aluminum-iron alloy element helically wound and embedded in a thermally conductive cement and powered at 208 3ϕ volts. These heaters are needed to maintain the test conditions (815^{o}C) because of heat loss between the induction heater and the chamber. Control is maintained by a set point controller operating a 208 3ϕ SCR.

Control System/Console

Almost all functions are controlled from the main control console. The control circuitry is designed around a programmable logic controller made by Texas Instruments. This provides the safety interlocks and sequencing functions required by the facility, and eliminates using a myriad of relays.

Time Sequence

The ESE sequencer is the heart of the system in that it sends the commands to the logic system to command forward flow, reverse flow, pulse flow, bleed-down, dust feed, counting, and recycle.

The sequencer has a small semiconductor memory in which it can store up to 32 "events", then associates a time and identifies which relay is triggered at that time. The relays are connected to the logic system, the cycle counters and the external time reset. A typical sequence is described below.

Facility in normal forward flow mode:

Event 00 would trigger relay 05 to stop the dust feeder table to purge the line and forward flow. Event 01 would trigger relay 01 to shut the inlet valve and bleed-down chamber pressure. Event 02 would trigger relay 02 to start reverse flow. Event 03 would trigger relay 03 to open pulse jet valve for 150 milliseconds. Event 04 would trigger relay 04 to advance the cycle counter. Event 05 would trigger relay 00 to restart forward flow and dust the feeder. Event 06 would trigger relay 15 to recycle sequencer.

TABLE 1. ESE SOURCE EVENTS

Source	Event
00	Restart forward flow and dust feeder
01	Start bleed-down
02	Reverse flow
03	Pulse flow
04	Cycle counter
05	Stop dust feeder and forward flow
15	Recycle sequencer

TABLE 2. EXAMPLE CLEANING SEQUENCE

Event	Source	Time	Description
00	05	00:00:01	Stop dust feeder and forward flow
01	01	00:00:04	Bleed-down
02	02	00:00:08	Reverse flow
03	03	00:00:09	Pulse
04	04	00:00:10	Count
05	00	00:00:11	Restart dust feeder and forward flow
06	15	00:10:11	Recycle

Data Recording

Two two-pen strip charts are used to display and store test system pressure and filter pressure drop.

One 24-point temperature strip chart is used to display and store various temperatures in the facility.

Theory

Barrier filtration with available ceramic fibers is a good technique for particle control at high temperature and pressure. To illustrate this, a short review and discussion of barrier filtration theory is helpful.

Figure 6 was taken from a report titled "Effects of Temperature and Pressure on Particle Collection Mechanisms: Theoretical Review" by Seymour Calvert and Richard Parker (EPA-600/7-77-002), January 1977. This figure shows a calculated fractional efficiency curve for a fiber bed. Minimum efficiency is indicated for a particle size of about 0.5 μm. The dip in the curve occurs because of the interaction of the three collection mechanisms applying to barrier filtration, direct interception, diffusion, and inertial impaction.

For particle size less than about 0.5 μm, collection by diffusion improves the efficiency of the filter bed. For particle size larger than about 0.5 μm, collection by inertial impaction increases the collection efficiency of the filter bed. This curve applies only to initial performance of a clean fiber bed, i.e., it does not include the increased collection efficiency that results from the filtration by the accumulating dust cake. Note on Figure 6, the No. 3 curve, indicating that the inertial impaction parameters for high temperature and pressure conditions, should show a small decrease in performance. To understand

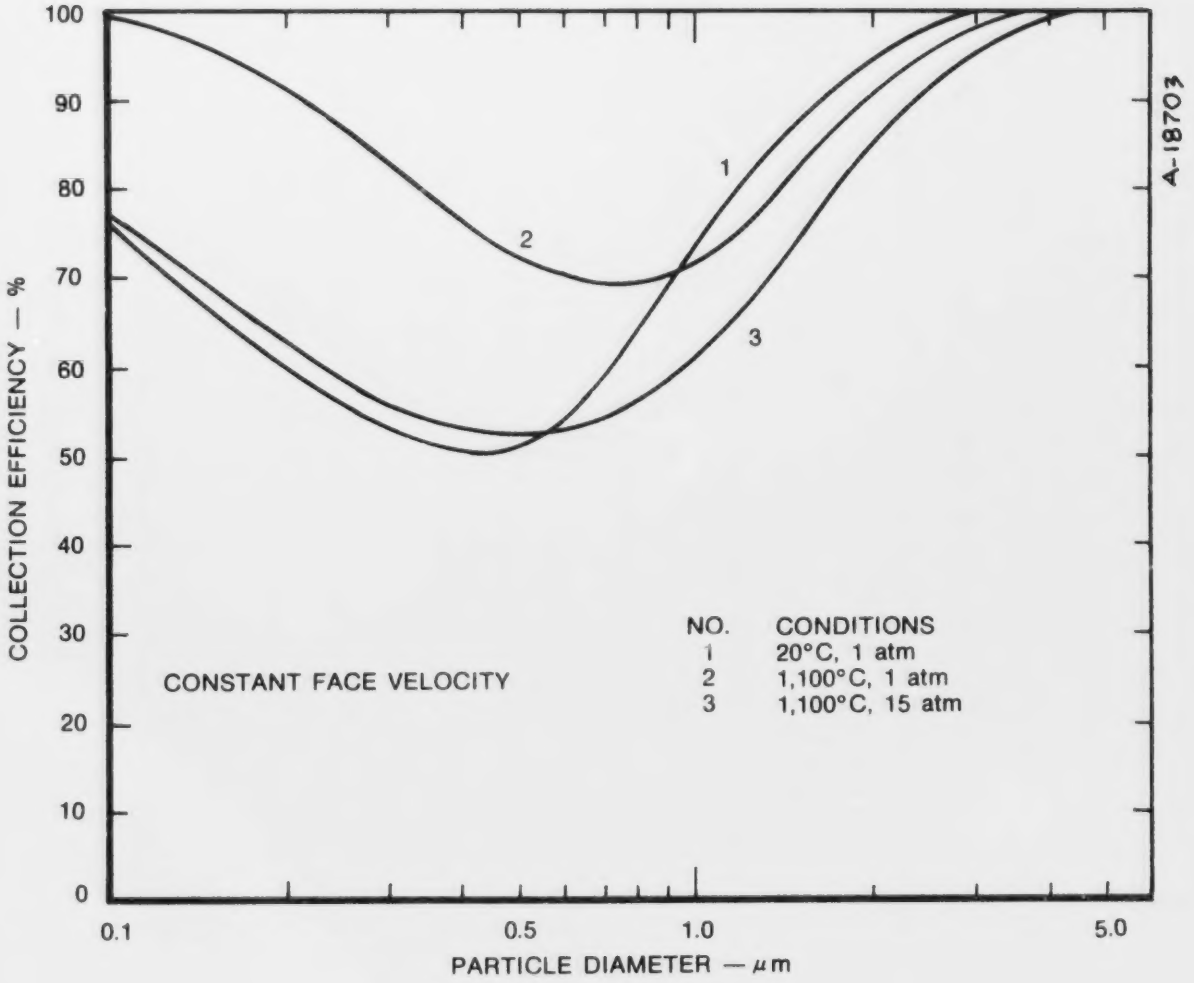

Figure 6. The effects of high temperature and pressure on the collection efficiency of a fiber bed.

the magnitude of this effect we can compare the performance of standard filter media when tested with dioctylphthalate smoke (DOP) to its performance when tested after a stabilized dust cake has been developed. A DOP smoke penetration test is a standard test given to measure the efficiency of high performance filters such as those used to filter "clean room" air or to collect biological contaminants. This test measures how efficiently a filter removes 0.3 μm diameter DOP smoke particles. Woven or felt filter media of the type commonly used for industrial filters will collect only 10 or 20 percent of 0.3 μm DOP smoke. After developing a dust cake, these same filter media will collect submicrometer particulate at an efficiency of greater than 90 percent. Thus, compared to the changes in performance in a filter media during the conditioning process, the changes predicted as a result of high temperature operation are small.

Ceramic fibers offer unique advantages for filtration, since many of these fibers have finer diameters than conventional filter fibers. Conventional fibers are ususally 10 or 20 μm in diameter, while ceramic fibers are available with average diameters of only 3.0 μm.

Collection efficiency can be improved simply by making a filter bed thicker, thus increasing the basis weight of the filter (its weight per unit area). However, to achieve high collection efficiency this way can lead to high operating pressure drops. Collection efficiency can also be increased by reducing the fiber diameter, which can result in decreased basis weight and filter bed thickness. The importance of fiber diameter is illustrated in the following equations describing the three primary particle collection mechanisms applicable to barrier filtration.

Interception parameters $K_I = \frac{d_p}{d_f}$

Impaction parameters $K_p = \frac{C'\rho_p d_p^2 U_g}{9\mu_g d_f}$

Diffusion parameter $K_d = \frac{C'kT}{3\pi\mu_g d_p U_g d_f}$

Although these equations describe the collection mechanisms, they are not collection efficiency equations. However, when expressed as above, an increase in any of the mechanism parameters (K_I, K_p, K_d) will result in an increase in efficiency.

The interception parameter is a function of fiber diameter. Changing from a 20 μm fiber to a 3.0 μm fiber will increase the interception parameter by a factor of 6.67 times.

The impaction parameter is a function of temperature and pressure essentially through changes in the gas viscosity (μg). For air, increasing temperature from 20 to 815°C increases viscosity by about 2.5 times, reducing the impaction parameter by a factor of 1/2.5 (or 0.4). However, the change in fiber diameter from 20 μm to 3.0 μm increases the impaction parameter by 6.67 times. The net effect of the two changes is to increase the impaction parameter by 2.7 times.

The diffusion parameter is a function of temperature and pressure through changes in the ratio of (C'T/μg). When operating at 815°C and 10 atm pressure, this ratio tends to either remain unchanged or increases slightly. The diffusion parameter is also a function of fiber diameter, and a change in fiber diameter from 20 μm to 3.0 μm will increase the diffusion parameter by 6.67 times.

From the above discussion it is evident that if we make a filter using 3.0 μm diameter ceramic fibers (which are commercially available),

we can reasonably expect that even at high temperature and pressure this filter will have high collection efficiency without excessive filter bed thicknesses or basis weights. Using the method developed by Torgeson, makes it possible to calculate collection efficiency for given particle size and fiber bed parameters. This calculation was performed for a 0.5 μm diameter particle with a density of 1.5 g/cm^3 (as measured at the Exxon miniplant), for gas temperature of 815°C, and for pressure at 10 atm. A fiber bed composed of alumina fibers with 3.0 μm diameter and fiber density of 2.8 g/cm^3 was assumed. Results of this analysis for two filtration velocities and two solidities (α - the volume fraction of the fiber bed which is solid) are plotted in Figure 7. This analysis indicates that a 3.0-μm diameter ceramic fiber filter bed, with a basis weight of 500 to 600 g/m^2, will collect submicrometer particulate with an initial (clean) efficiency of about 90 percent at high temperature and pressure. As previously stated a typical industrial filter media (20-μm fibers) collects such particles at only 20 percent efficiency for the same basis weight. In a different view you can see that to achieve collection efficiency comparable to commerical industrial media will require a ceramic fiber filter media with weights only one-tenth that of the commercial media. Another interesting feature of the analysis is that efficiency decreases for increasing velocity. However, by adding fibers, the given efficiency can be maintained as velocity is increased. The quantity of required additional fiber is relatively small, especially if only 20 percent initial efficiency is adequate for a 0.5-μm particle.

Most commerically available ceramic fiber structures are produced for insulation applications. Consequently, these materials are generally characterized by an open fibrous structure, i.e., they have low solidity,

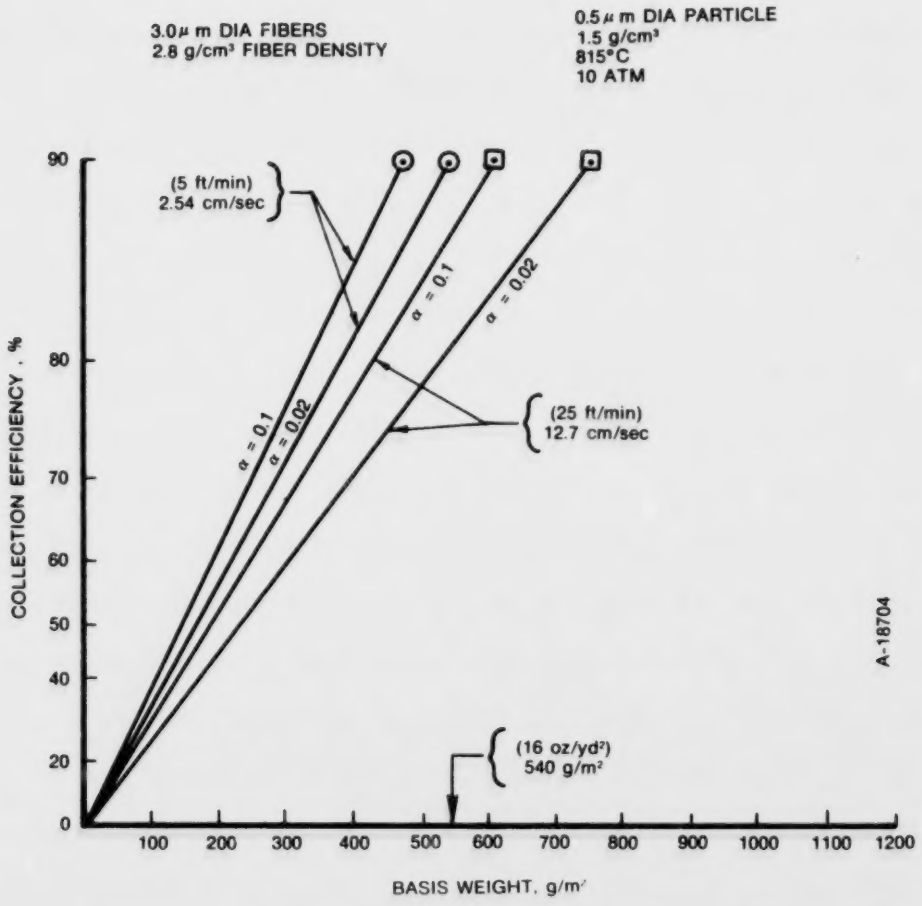

Figure 7. Calculated performance of 3.0 μm alumina fiber bed.

with perhaps only 2 percent of the volume occupied by fibers (α = 0.02). A solidity of α = 0.10 is more typical of a structure designed for filtration. Figure 8 shows the effect on fiber bed thickness for changes in solidity and air-to-cloth ratio. For solidity typical of insulation materials (α = 0.02), a fiber bed about 1 cm thick should achieve high initial collection efficiency of submicrometer particulate, while a more compressed media with α = 0.10 would achieve this efficiency with a bed thickness of only 2 mm. If efficiency typical of industrial filters is adequate, very thin layers of the 3.0-μm diameter fibers will suffice. Also note that filter media thickness is not a strong function of air-to-cloth ratio, indicating the possibility of high filtration velocity. Higher filtration velocity results in increased pressure drop, which may be acceptable in a PFBC application.

Room Ambient Filter Media Tests

A large number of ceramic fiber filter media candidates were subjected to a series of filtration tests at room ambient conditions. These tests shown below, include some examples of conventional filter media for comparison.

- Dioctylphtalate (DOP) smoke penetration as a function of airflow velocity
- Determination of maximum pore size in μm
- Measurement of permeability
- Flat-sheet dust loading tests using AC fine test dust; overall collection efficiency and dust loading required to develop 3.7 kPa (15 in. H_2O) pressure drop are determined from this test, operated at 10 cm/sec (20 ft/min) air-to-cloth ratio

Data collected from these tests are summarized in Table 3.

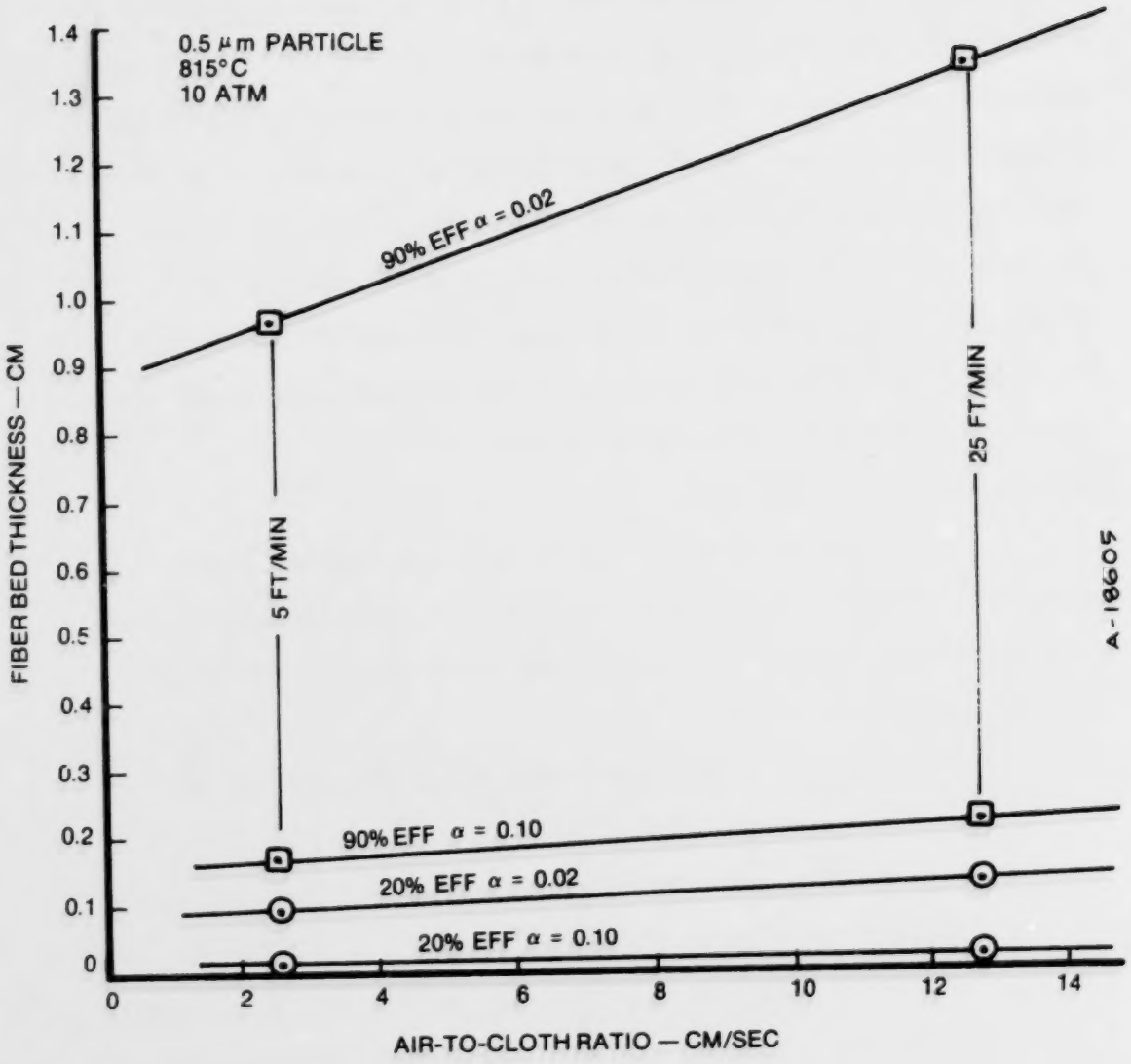

Figure 8. Fiber bed thickness.

TABLE 3. SUMMARY ROOM AMBIENT TEST DATA

(W) Woven (P) Paper (F) Felt	Basis Weight g/m^2	Efficiency on ACF @ 10 cm/sec (20 ft/min)	Dust Loading g/m^2 to 3.735 kPa (g/ft^2 to 15" H_2O)	Permeability $cm^3/sec/cm^2$ for 0.1245 kPa ($ft^3/min/ft^2$ for 0.5" H_2O ΔP)	Maximum pore size micrometers	Percent Efficiency on 0.3 μm D.O.P. at cm/sec		
						2.68	5.35	14.22
1. Carborundum Fiberfrax cloth (W) with nichrome wire insert	1366	96.55	240.0 (22.2912)	8.687 (17.1)	248.6	45	47	50
2. Zircar Zirconia felt ZFY-100 (P)	615	95.64	Media Fractured	10.861 (21.38)	59	75	78	72
3. ICI Saffil alumina paper (P)	165	99.805	159.4	9.307	43	82	65	62
4. ICI Saffil mat (P)	355	98.74	Media Fractured	12.395 (24.4)	61.1	79	80	73
5. Babcock & Wilcox Kaowool (F)	746	98.464	118.2 (10.980)	8.067 (15.88)	66.9	96.5	93.5	86
6. Carborundum Fiberfrax (F) durablanket	1363	99.507	147.0 (13.6523)	5.583 (10.99)	68.2	97.1	94.6	90.5
7. Johns Manville Fiberchrome (F)	1297	99.654	253.9 (23.59)	11.897 (23.42)	112.3	78	73	74
8. Stevens Astroquartz (W) style 581	283	60.77	Test Stopped — Low Eff.	37.236 (73.3)	248.6	0	9	12
9. Hitco Refrasil C-100-96 (W) heat cleaned	1284	81.97	5.9 (0.5482)	1.240	112.3	0	19	34
10. Hitco Refrasil C-100-48 (W) not heat cleaned	667	83.37	11.6 (1.074)	3.099 (6.1)	133.8	0	11	10
11. Stevens Astroquartz cloth (W) style 570	677	56.83	Test Stopped — Low Eff.	22.758 (44.8)	267.7	0	13	32
12. 3M AB-312 basket weave (W) cloth	311	51.38	Test Stopped — Low Eff.	13.553 (26.68)	870	0	5	8

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TABLE 3. Continued

(W) Woven (P) Paper (F) Felt	Basis Weight g/m^2	Efficiency on ACF @ 10 cm/sec (20 ft/min)	Dust Loading g/m^2 to 3.735 kPa (g/ft^2 to 15" H_2O)	Permeability $cm^3/sec/cm^2$ for 0.1245 kPa ($ft^3/min/ft^2$ for 0.5" H_2O ΔP)	Maximum pore size micrometers	Percent Efficiency on 0.3 µm D.O.P. at cm/sec		
						2.68	5.35	14.22
13. 3M AB-312 twill weave (W) cloth	231	48.55	Test Stopped – Low Eff. (same)	28.448 (56)	435	0	3	2
14. Hitco Refrasil cloth (W) UC-100-48	643	69.25	21.3 (1.98024)	8.687 (17.1)	193.3	0	4	3
15. Zircar Zirconia cloth (W) ZFY-30A	608	99.014	88.1 (8.1853)	5.791 (11.40)	248.6	29	37	34
16. FMI-Stevens Astroquartz (W) cloth crowfoot satin	352	76.19	91.6 (8.5057)	16.556 (32.59)	267.7	0	5	6
17. 3M AB-312 twill weave (W) cloth coated with 3M coating	227	47.64	Test Stopped – Low Eff.	65.181 (128.31)	870	0	3	10
18. 3M AB-312 basket weave (W) cloth coated with 3M coating	281	45.65	Test Stopped – Low Eff.	47.595 (93.69)	580	0	7	0
19. 3M AB-312 twill weave (W) cloth Menarde coating	254	55.078	Test Stopped – Low Eff.	51.211 (100.81)	580	0	6	10
20. Hitco Refrasil cloth (W) UC-100-96 not heat cleaned	1249	68.46	13.7 (1.2708)	3.414 (6.72)	316	0	11	16
21. Carborundum Fiberfrax (W) no insert wire L-126TT	1544	99.21	173.5 (16.1213)	7.447 (14.66)	91.6	55	55	57
22. Hitco Refrasil batt B100-1 (F)	807	99.229	169.1 (15.706)	8.900 (17.52)	64.4	84	79	72
23. Hitco Refrasil standard (W) not heat cleaned uc-100-2B	335	84.41	22.9 (2.1257)	11.897 (23.42)	139.2	0	1	0
24. Hitco Irish Refrasil (W) chromized C-1554-48	683	81.476	12.0 (1.1116)	5.121 (10.08)	124.3	2	8	10

T-889(a)

TABLE 3 Concluded

(W) Woven (P) Paper (F) Felt	Base Weight g/m^2	Efficiency on ACF @ 10 cm/sec (20 ft/min)	Dust Loading g/m^2 to 3.735 kPa (g/ft^2 to 15" H_2O)	Permeability $cm^3/sec/cm^2$ for 0.1245 kPa ($ft^3/min/ft^2$ for 0.5" H_2O ΔP)	Maximum pore size micrometers	Percent Efficiency on 0.3 μm D.O.P. at cm/sec		
						2.68	5.35	14.22
25. Carborundum Fiberfrax (P) paper (with binder) 970J	604	99.99	73.7 (6.8442)	26.899 (52.95)	47.7	99.5	99.0	97.6
26. ICI Saffil Zirconia paper (P) (with binder)	212	93.20 (Probable hole)	82.2 (7.6374)	8.692 (17.11)	37.4	83	78	74
27. Carborundum Fiberfrax (P) paper (no binder) 970-AH	152	99.91	84.4 (7.8369)	12.416 (24.44)	43.5	88	-	73
28. 3M AB-312 double thick (W) plain weave	1035	43.86	Test Stopped – Low Eff.	84.836 (167)	Too large to measure with our equipment	0	10	41
29. FMI crowfoot satin cloth (W) Astroquartz	905	40.08	Test Stopped – Low Eff.	62.078 (122.20)	497	0	10	32
30. 3M AB-312 12 harness satin (W) weave	675	53.73	Test Stopped – Low Eff.	75.529 (148.68)	696	0	8	24
31. 630 Tuflex fiberglass# (W)	564	93.982	47.6 (4.4187)	16.038 (31.57)	174	10	9	19
32. 15-011-020 woven filament# (W) polyester	175	96.076	28.0 (2.60163)	6.828 (13.44)	74	6	0	4
33. 25-200-070 polyester felt# (F)	524	99.193	135.3 (12.5688)	11.897 (23.42)	128.9	34	24	29
34. Hitco Refrasil cloth (std) (W) not heat cleaned, med. thickness	637	48.40	34.5 (3.2063)	6.934 (13.65)	-	-	-	-

#These materials are conventional (not ceramic) media.

T-889(b)

Penetration tests using DOP smoke measure the ability of the clean fiber bed to stop fine particles. The DOP smoke generator is adjusted to provide a nominal particle size of 0.3-μm diameter, a "most penetrating" particle size because of the minimal effect of diffusion and inertial impaction at this size. The DOP test results should correlate well to the predicted results by analysis since particle collection is provided only by the fibers and not by the dust cake. Figure 9 provides a plot of the DOP efficiency as a function of airflow velocity for all the media tested. Ceramic media data are plotted in solid lines, and conventional media are plotted in dotted lines. Numbers on the curves correspond to those in Table 3. Some observations concerning this data are:

- Several of the ceramic materials, especially the ceramic papers and felts, are capable of higher efficiency collection of fine particles than media normally used successfully in commerical filter units
- Many of the woven ceramic materials had zero DOP efficiency at low velocity, and higher DOP efficiency at higher velocity

  This point is contrary to what theory suggests and to the behavior normally seen in tests of conventional filter materials. A probable explanation for this is that it is caused by many large pores present in the media. Examination of the pore size data in Table 3 shows that the woven ceramic materials group is characterized by larger pore sizes than that of conventional filter materials. Thus, at low airflow velocity, most of the flow passes through the large pores and little filtration takes place. As velocity is increased, flow through the large pores becomes relatively restricted resulting

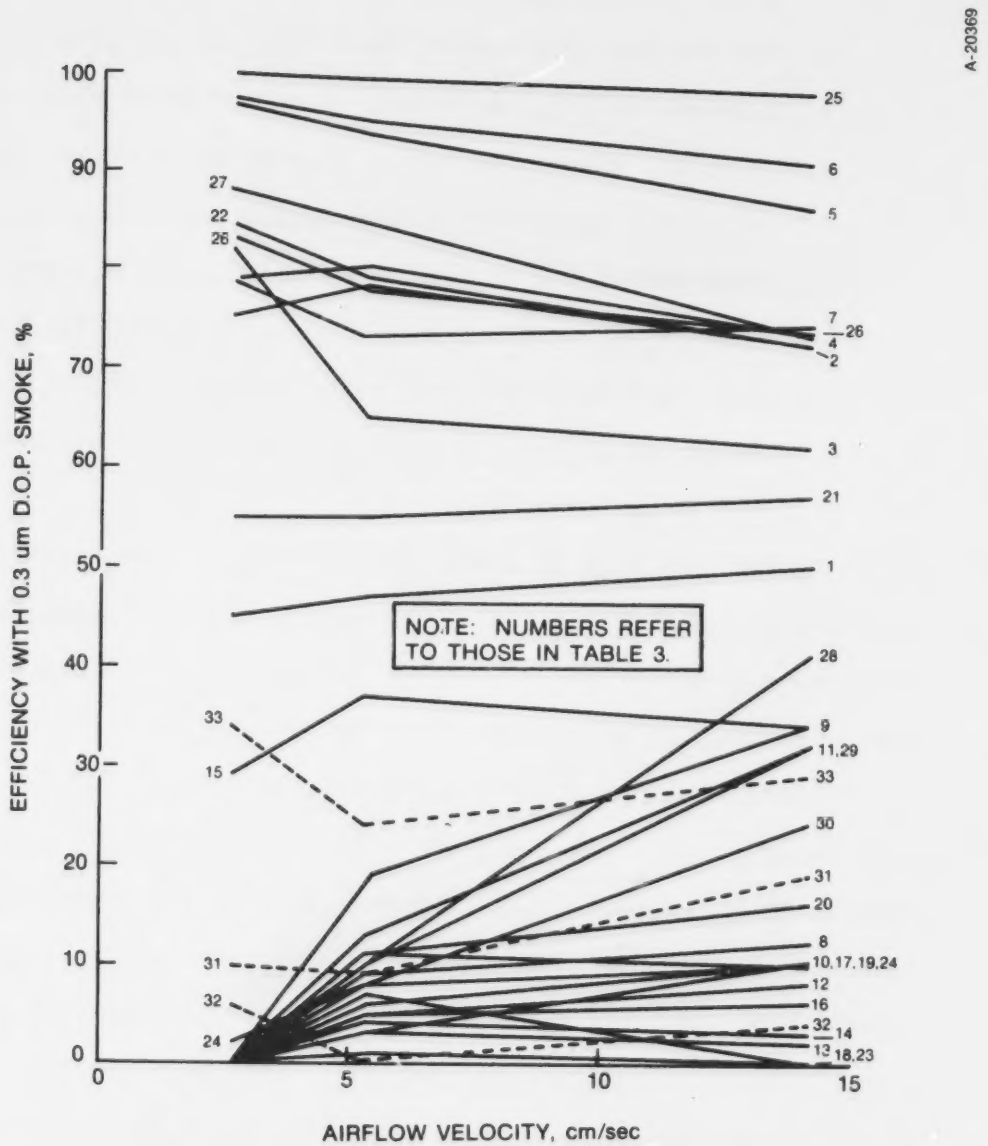

Figure 9. DOP efficiency airflow velocity.

from increased ΔP caused by high velocity through the pores, and some of the flow is forced to pass through smaller pores where more filtration can occur.

- The DOP data also support the theoretical analysis in the previous section. Efficiency as a function of basis weight for selected ceramic materials is plotted in Figure 10. The selected materials are ceramic papers and felts providing a fiber bed similar to that on which the analysis summarized in Figure 5 was based. Figure 10 illustrates that the nominally 3 μm fibers provide higher collection efficiency on a weight-per-unit-area basis than conventional media produced with larger diameter fibers.

Maximum pore size data show that many of the woven ceramic materials had pores larger than those characteristic of conventional filter materials, and many of the felt and paper materials had pore sizes similar to those of conventional filter materials.

Permeability is measured as the flow per unit area at a constant pressure drop. Thus, a material with low permeability offers a high restriction to gas flow and one with high permeability allows more gas to penetrate for a given pressure drop. Table 3 shows that some ceramic materials are available which have low permeability while others have high permeability. Some of the woven materials have low permeability and large pore size, and again, others have high permeability and large pore size. Most of the paper and felt materials have permeability similar to that of commonly used filter materials.

Flat-sheet dust loading tests were performed as follows: a 7.62 cm (3 inch) diameter disc of media was suspended across an air stream which

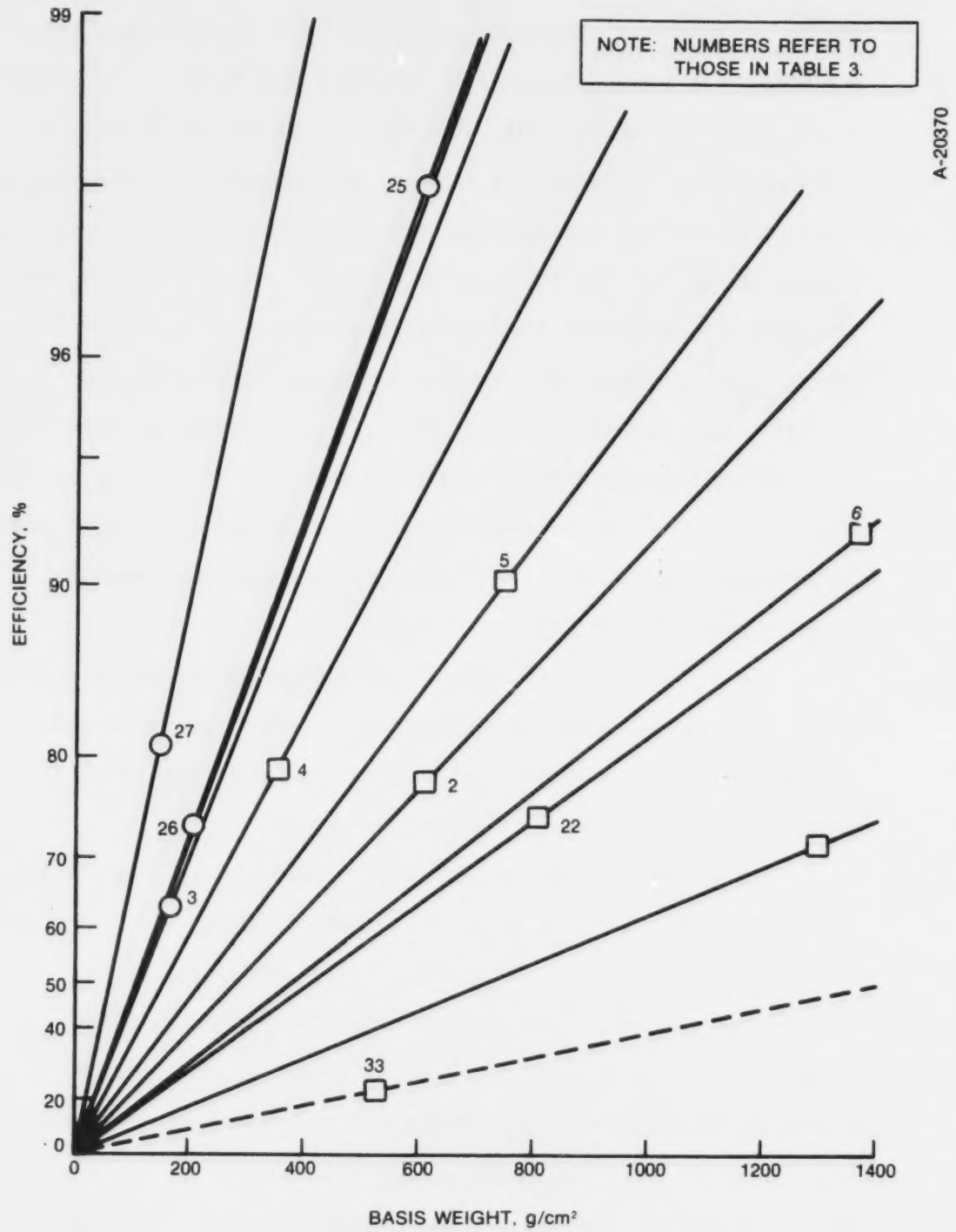

Figure 10. DOP efficiency test data.

was maintained at 10.16 cm/sec (20 ft/min) velocity through the filter media. In this test, the media supported itself against the pressure drop (no screen was used). Standard AC fine test dust (0-80 μm silica) was fed to the media at a nominal rate of 0.883 g/m^3 (0.025 g/ft^3) until a pressure drop of 3.735 kPa (15 in. H_2O) was reached. Pressure drop as a function of time was monitored during the test. This data is presented in Figures 11, 12, and 13. for selected materials. From this data, dust loading (g/m^2) necessary for a given pressure drop of 3.735 kPa (15 in. H_2O) is determined. Examination of the data in Table 3 indicates that some of the woven materials reached high pressure drops while collecting only a small weight per unit area of dust, as well as that of the commerical woven materials (items 31 and 32). Other woven ceramics were penetrated so severely that they would not develop a pressure drop of 3.735 kPa (15 in. H_2O).

Two of the non-woven samples (which were unsupported) fractured as a result of the pressure drop across them. Several of the ceramic paper and felt materials exhibited dust loading similar to that which is expected from conventional filter papers and felts.

The flat-sheet loading tests also provided overall collection efficiency (mass basis) data for the tested materials. Dust penetrating the media was collected in an absolute filter downstream of the test media. Table 3 reveals that most of the woven ceramic materials did not achieve high collection efficiency in this test. Conversely, woven commerical materials were only moderately efficient. However, several of the ceramic paper and felt materials provided collection efficiency of 99 percent or better. The two materials which fractured would have provided

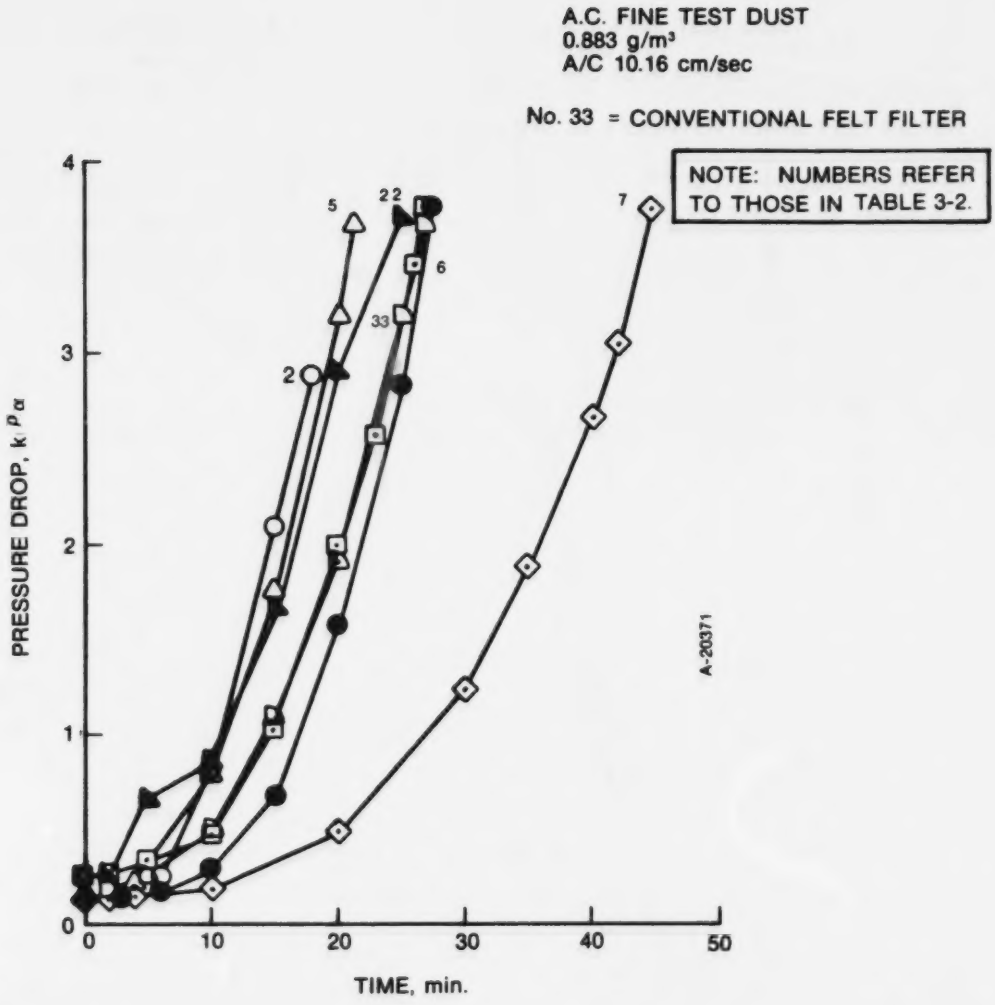

Figure 11. Dust loading of ceramic felts.

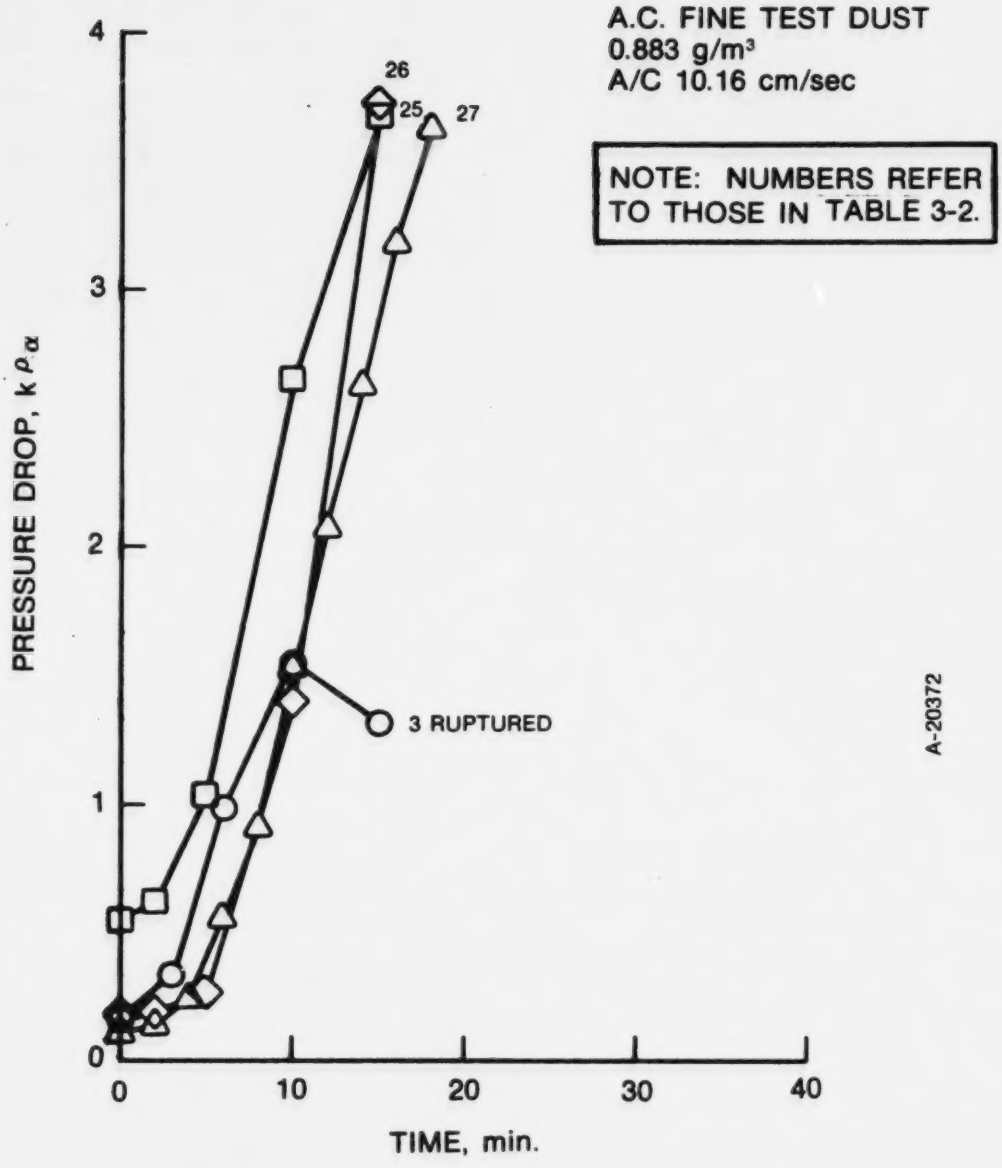

Figure 12. Dust loading of ceramic paper.

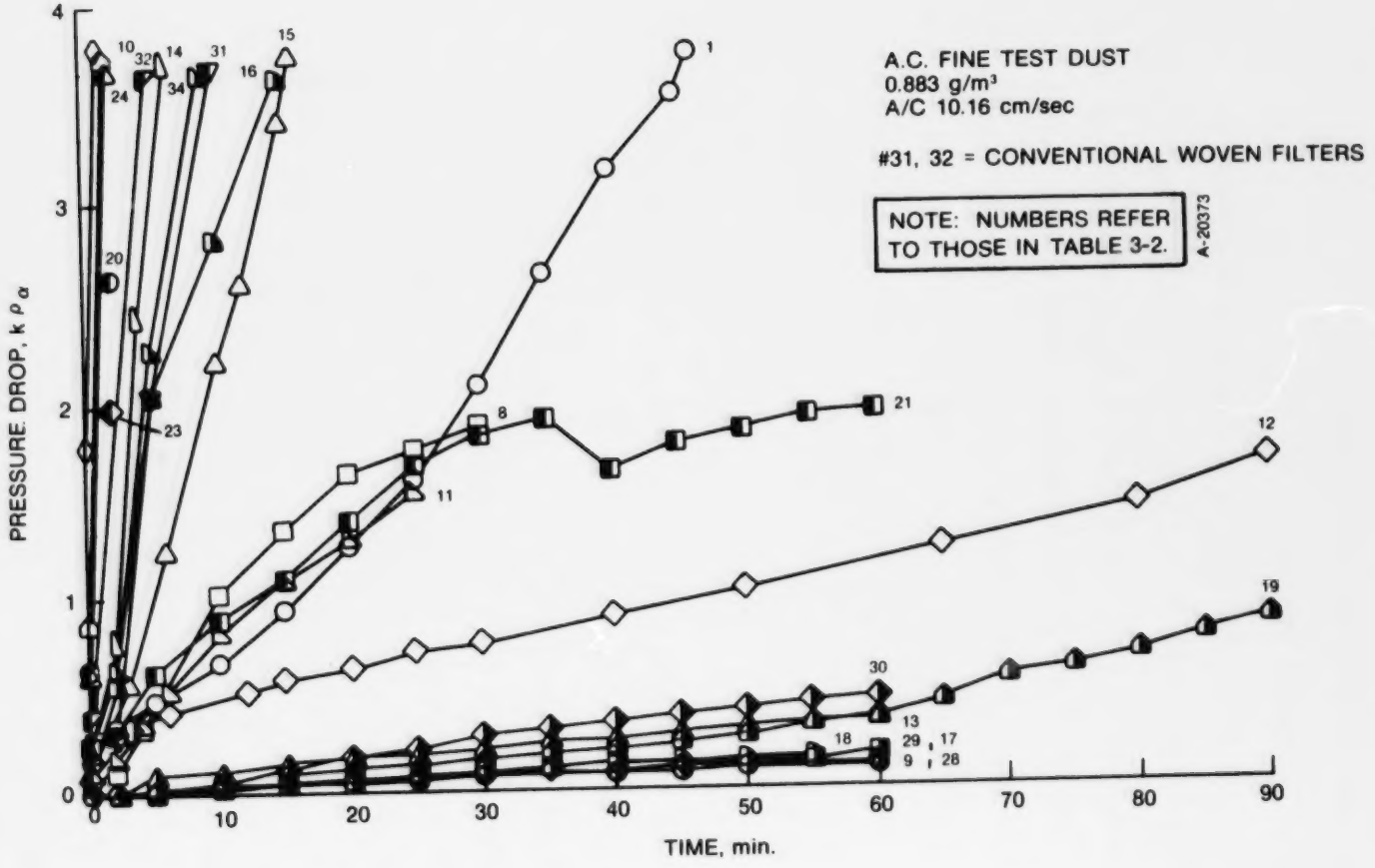

Figure 13. Dust loading of woven ceramic media.

higher efficiency performance if they had not fractured, the test was stopped upon detection of the fracture.

Mechanical Screening Test Data

As previously stated, the available ceramic fiber structures can be generally classed into three groups: woven, paper, and felt. During the preliminary testing, all three types of media were subjected to survey tests. The objective of the mechanical screening tests was to subject the media to typical filter-cleaning loads in the high temperature and pressure environment and to determine which media can survive these loads. All the mechanical screening tests were operated at an air-to-cloth ratio of 2.54 cm/sec (5 ft/min).

Woven Media Tests

Three woven media types were tested, and their results are summarized in Table 4. These tests were performed early in the program before we had fully proved the 815^{o}C capability of the heater. Since these tests are fairly qualitative, the following photographs and discussion are offered to augment the data in Table 4.

The AB-312 media test was terminated because of excessive dust penetration through the relatively large pores around the yarn filament of the cloth. This media clearly showed a clean separation of the dust cake from the media surface (Figure 14 illustrates this effect, seen on other tests as well).

An Irish refrasil filter was tested with pulse cleaning after surviving 195 reverse-flow cycles. This media developed holes during the pulse testing. Examination after 3,100 pulse cycles revealed the condition illustrated in Figures 15 and 16. The holes were generally located near the center of the openings formed by the support cage,

TABLE 4. WOVEN MATERIALS TEST RESULTS

	Temperature	Cleaning	Cycles	Time	Failed
3M Company AB-312 Twill Weave	538°C	Reverse Flow	153	8.5 hr	No
Irish Refrasil Silica/Chrome Satin	538°C 538°C	Reverse Flow Pulse 1400 kPa (200 psi) 100 mS	195 3100	13 hr 7 hr	No Yes, holes
Irish Refrasil Silica/Chrome Satin	538°C 815°C	Reverse Flow Pulse 1100 kPa (160 psi) 1100 mS	100+ 1	15 hr --	No Seam

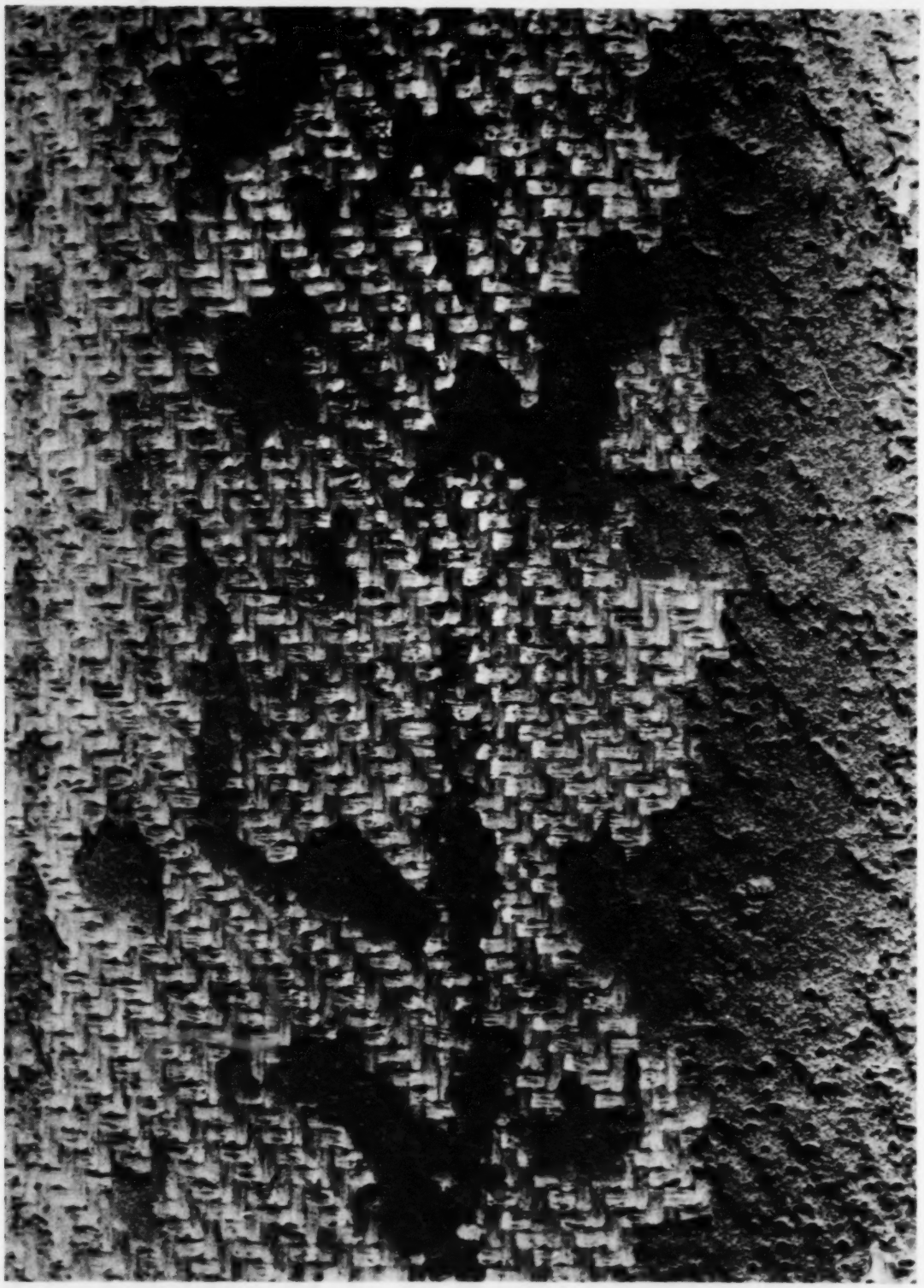

Figure 14. Post-test dust cake -- Test B103 3M-AB312 twill weave.

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Figure 15. Irish Refrasil pulse test failure.

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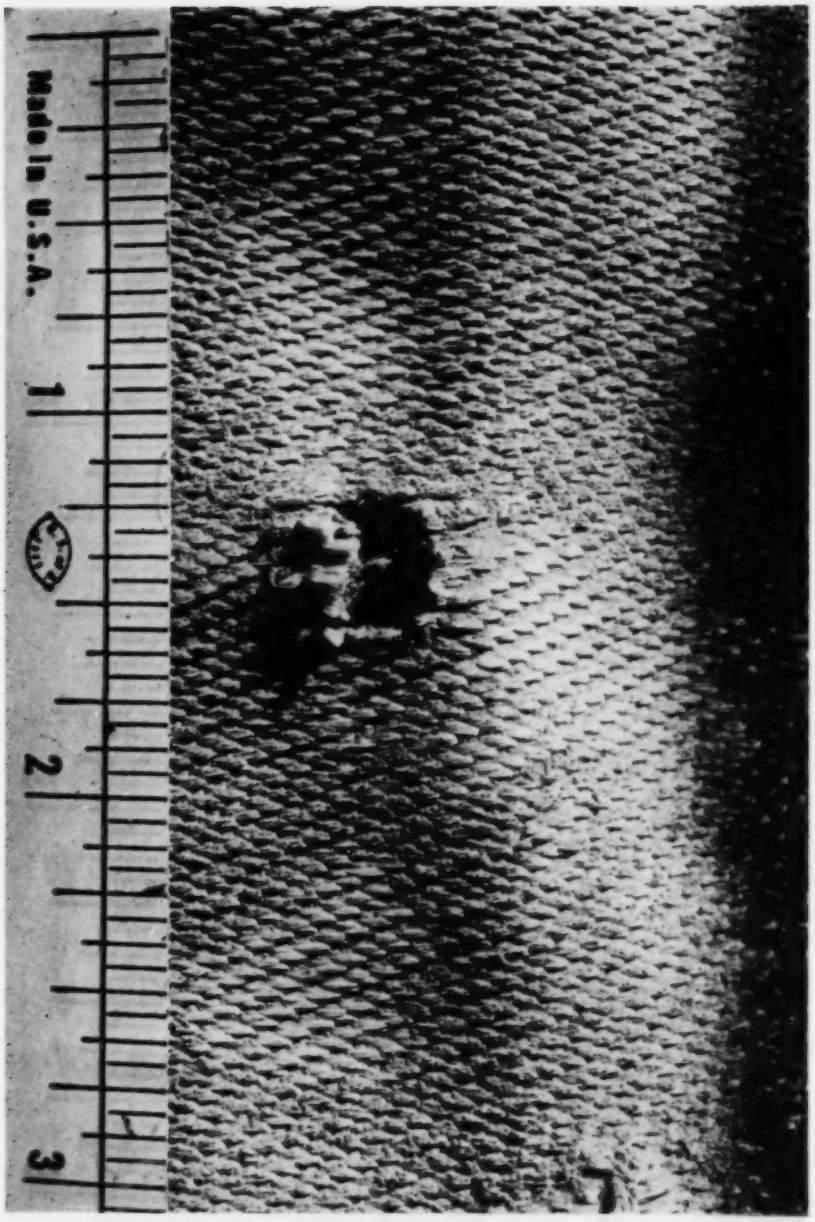

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Figure 16. Irish Refrasil pulse test failure.

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appearing to be a result of bending and shock at the maximum points of media acceleration during cleaning. This effect could possibly be controlled by making the support cage openings smaller. Table 4 shows an 1100-m/sec pulse duration, which occurred because of an error in setting the pulse duration, and was not discovered until after the test. This could also have caused the media failure. In addition, it should be noted that pulse cleaning is probably not required for woven media since the less rigorous reverse-flow cleaning can remove the dust cake.

Figure 17 shows a seam failure occurring on the first pulse, and illustrates the force of the pulse. This particular test element had been installed several times and, therefore, had been handled more than usual. (Failure can be caused by excess handling and sharply bending the fiber).

Paper Media Tests

Only one test of paper media was performed. Results of this test are summarized in Table 5. There were no evident failures after a short reverse-flow test; however, the media did not survive pulse testing. A bias-cut wire screen supported this media on both surfaces. The bias-cut allowed the tubular shape of the element to stretch, contributing to its failure. A straight-cut screen would provide better support for paper media. Figures 18 and 19 show the bias-cut screen with several tears in the media.

Felt Media Tests

Test results for felt media are summarized in Table 6. In the first test, no damage was evident as a result of reverse-flow testing. After about 5,000 cycles of pulse testing, the pressure-drop monitor indicated a problem. Visual examination revealed that the lower band clamp had slid upward, allowing a leak under the filter element. After

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Figure 17.

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TABLE 5. PAPER MATERIALS TEST RESULTS

	Temperature	Cleaning	Cycles	Time	Failed
ICI	815°C	Reverse Flow	21	1 hr	No
Saffil Alumia	815°C	Pulse 1100 kPa (160 psi) 100 mS	496	9 hr	Yes

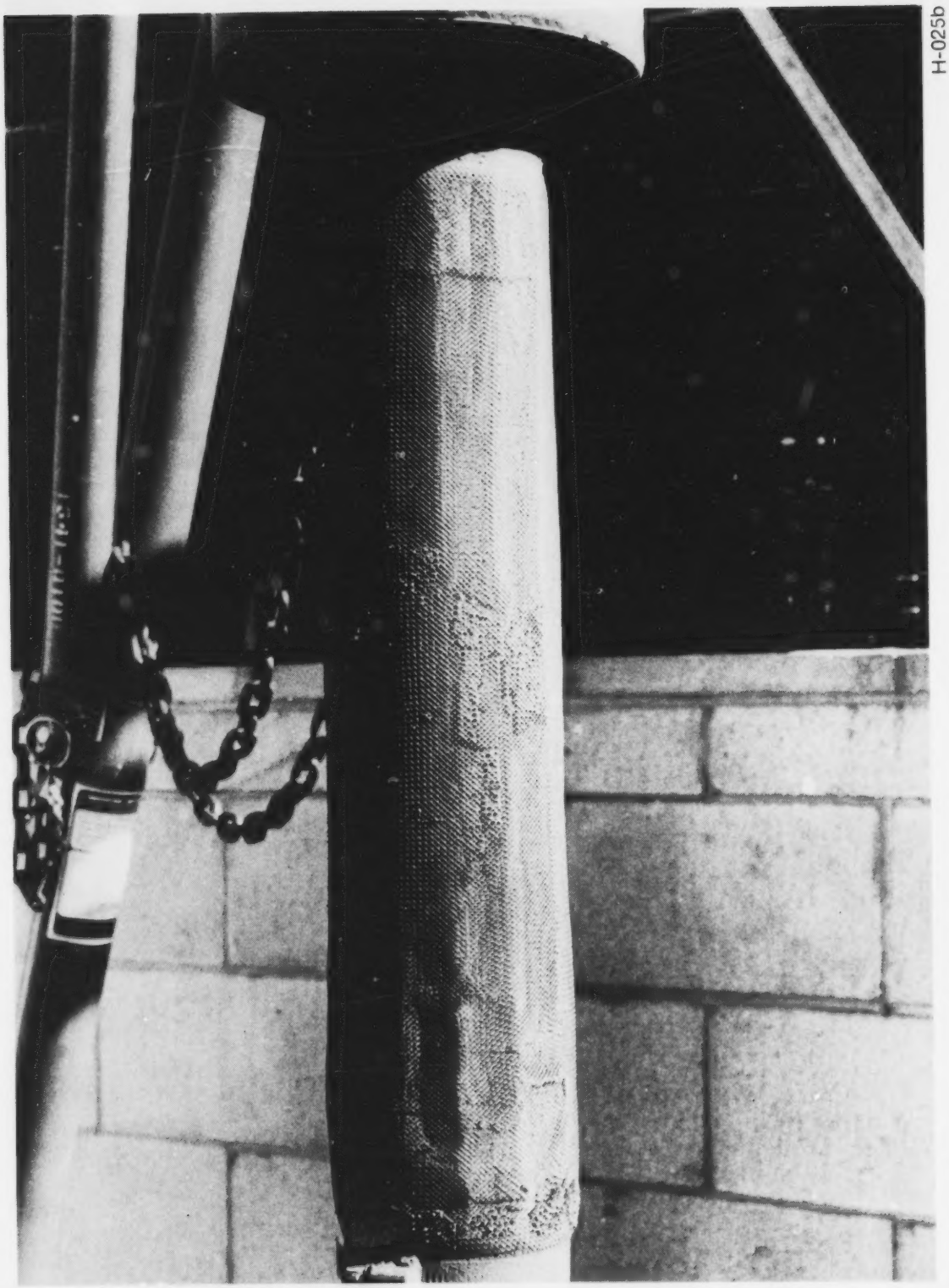

Figure 18. Saffil alumina paper after pulse testing.

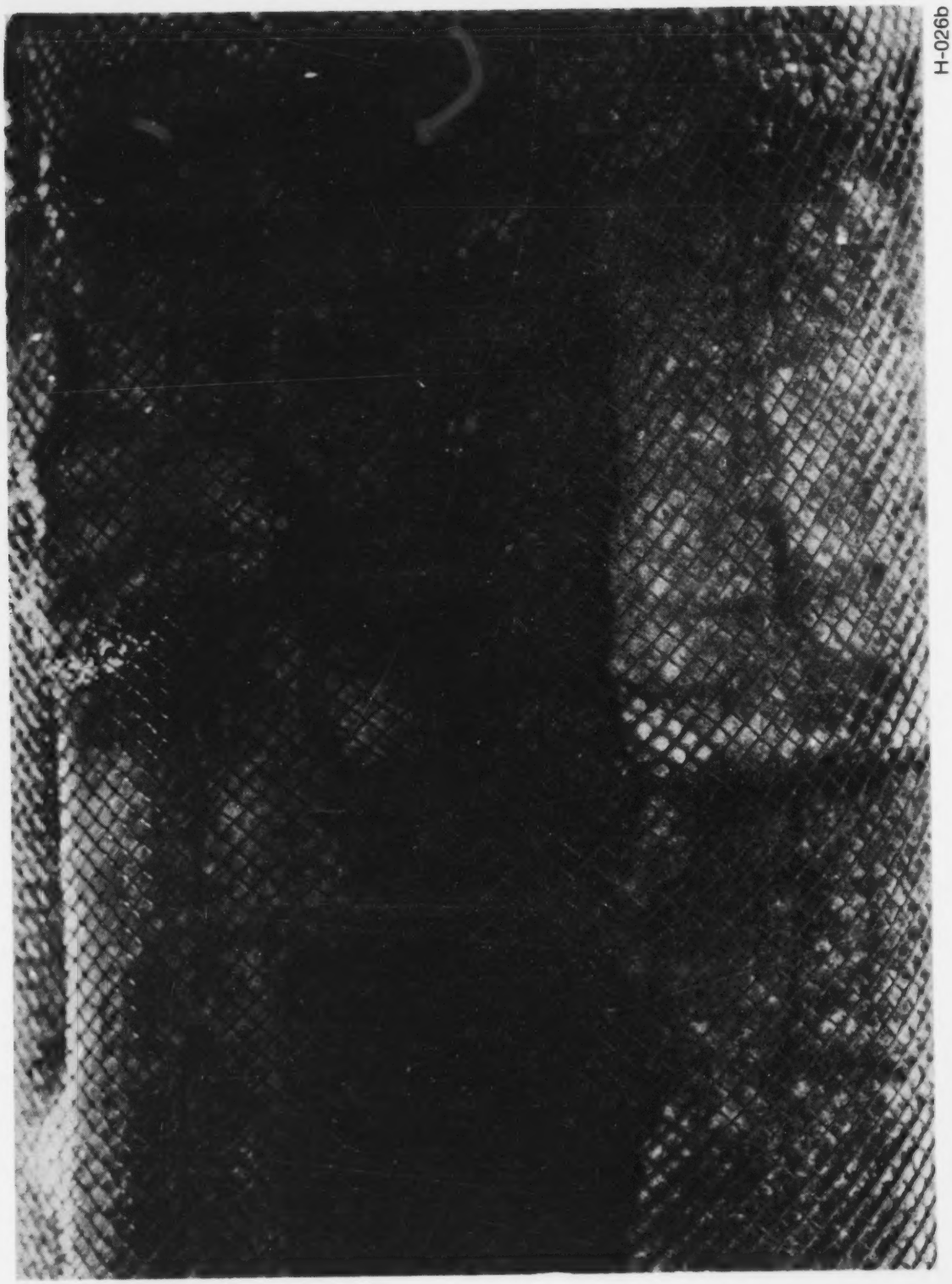

Figure 19. Saffil alumina paper after pulse testing.

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TABLE 6. FELT MATERIALS TEST RESULTS

	Temperature	Cleaning	Cycles	Time	Failed
ICI Saffil Alumina	815°C 815°C	Reverse Flow Pulse 1100 kPa (160 psi) 100 mS	75 9405	3 hr 49 hr	No Yes, seam
ICI Saffil Alumina	815°C	Pulse 1100 kPa (160 psi) 100 mS	7450	38 hr	No
ICI Saffil Alumina	815°C	Pulse 1100 kPa (160 psi) 100 mS	50,000	140 hr	No
Fiberfrax Cloth with Nichrome wire scrim	815°C	Pulse 1100 kPa (160 psi) 100 mS	50,000	140 hr	No
Fiberfrax Blanket	825°C	Pulse 1100 kPa (160 psi) 100 mS	50,000	140 hr	No

the lower end of the media was reclamped, the tests continued. The lateral seam for this media was accomplished by rolling a flat sheet of media into a cylinder and overlapping the ends. This tube shape was supported inside and out by a wire screen. After a total of 9,405 pulse cycles, visual examination showed that the seam had separated by sliding apart, which was probably started when the band clamp moved earlier in the test. The flexible bias-cut support screen also contributed to this problem. Figures 20 and 21 show the element and a close-up of the seam separation. The whiteness shown in Figure 21 indicates a good separation of the dust cake from the media surface. The area was cleaned by tapping the screen several times with a pencil.

For the second test, a screen with a fine diameter wire with more strands per unit length was used to support the media. While this screen was also cut on the bias, it provided a stiffer support for the media. Extra care was taken to ensure that the clamps were tight. This media operated for 7,450 pulse cycles with no apparent damage. The test was stopped because of a failure of the test rig heater element. Figure 22 is a photo of the element after the test.

Three additional ceramic filter media configurations survived a test during which the filter elements were subjected to 50,000 cleaning pulses. The objective of these tests was to simulate approximately 1 year of mechanical cleaning cycles on the media at high temperature and pressure. Test conditions were:

Temperature: 815^{o}F

Pressure: 930 kPa

Air-to-cloth ratio: 5 to 1 (2.54 cm/sec)

Cleaning pulse pressure: 1100 kPa

Figure 20. Saffil alumina felt bag post-test.

Figure 21. Separated seam.

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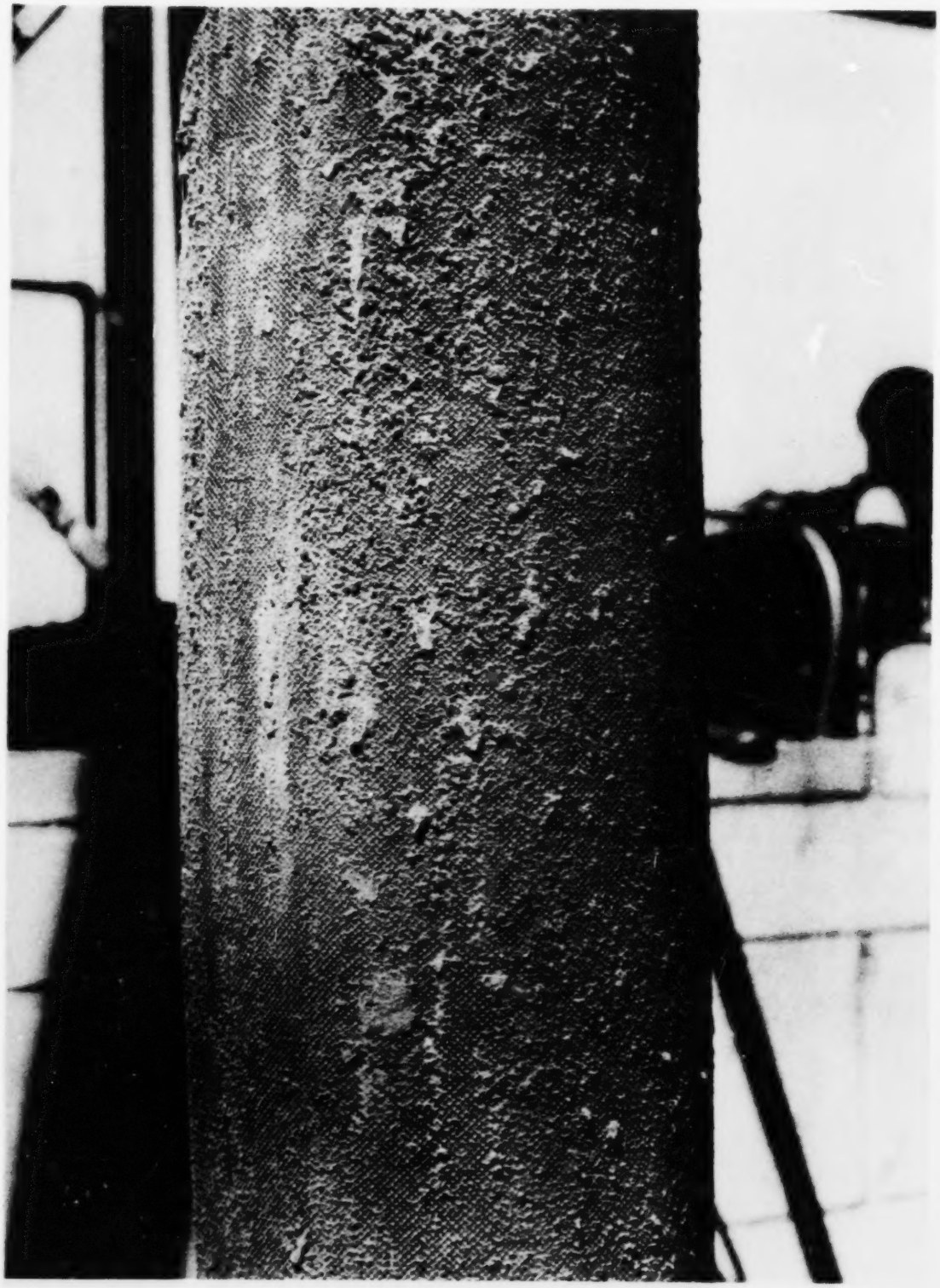

Figure 22. Saffil alumina blanket after pulse tests.

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Cleaning pulse interval: ~10 seconds

Cleaning pulse duration: 0.1 sec

Dust: recirculated flyash

The three filter media configurations tested were:

- Saffil alumina mat within an inside and an outside layer of 304 stainless steel knit wire screen. Figure 23 shows how easily the residual dust cake was removed from this media after the test.
- Woven Fiberfrax cloth with nichrome wire scrim insert. Figure 24 shows the dust cake following the 50,000 pulse test. This woven material performs more like a felt because the yarns are "fuzzy".
- Fiberfrax blanket within an inside and outside cylinder of 304 stainless steel wire mesh screen similar in construction to common window screen. The ceramic fiber blanket was held in position between the screens with 302 ss wire sewn between the screens. This resulted in about 100 penetrations of the ceramic fiber bed. Figure 25 shows the dust cake following the test.

Pressure drop during the tests was controlled by the rapid cleaning pulses and in general remained less than about 5 kPa (20 in H_2O).

Dust penetrating the ceramic test media was collected on a high efficiency filter located downstream (after cooling) of the test chamber. This data is not reported for the Saffil alumina or for the woven Fiberfrax cloth because of the leak discovered in a gasket in the test rig. This problem was corrected before the Fiberfrax blanket test was performed. Average outlet loading during this test was 0.0055 $g/_am^3$

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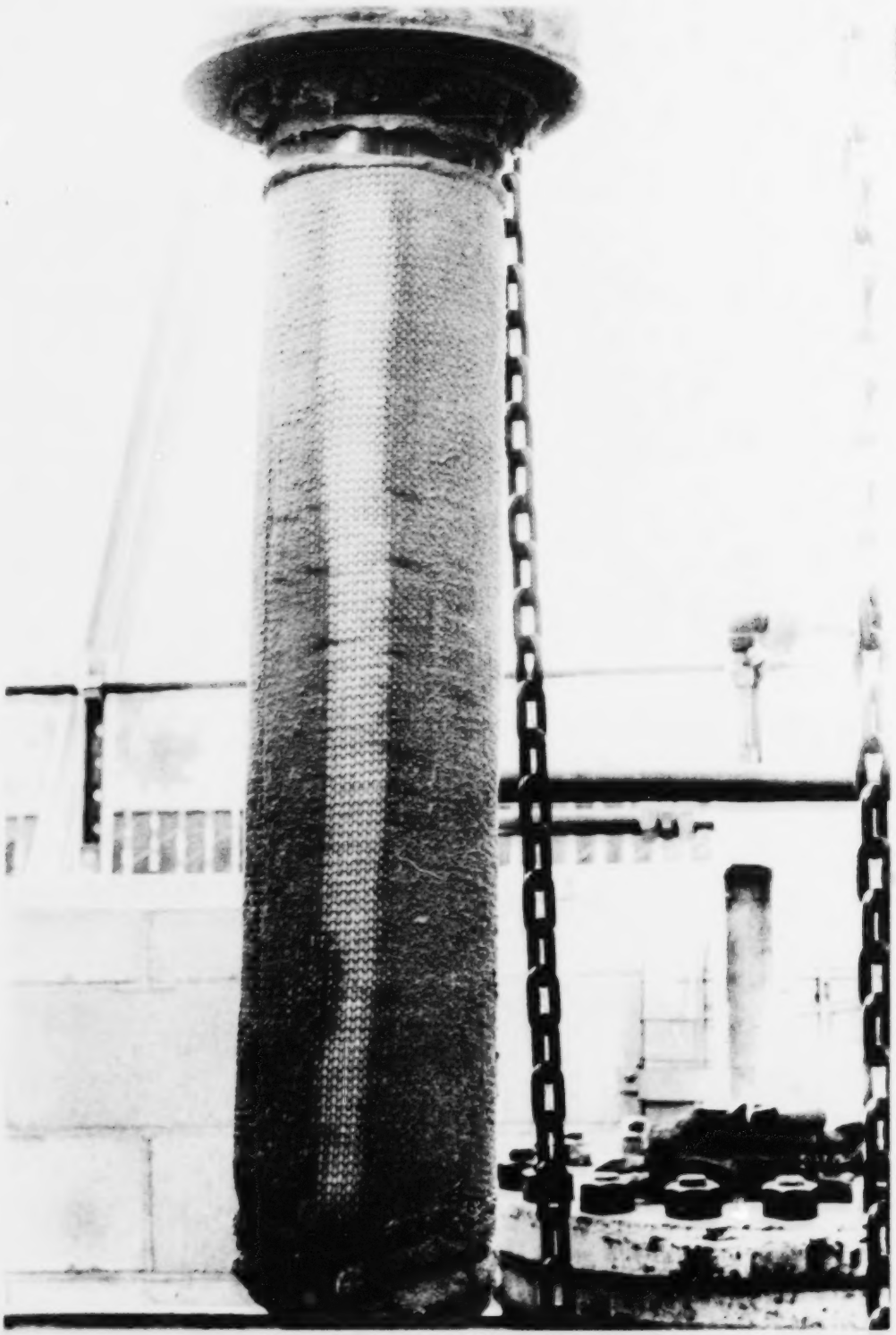

Figure 23. Saffil alumina -- post-test dust cake (clean strip using vacuum cleaner).

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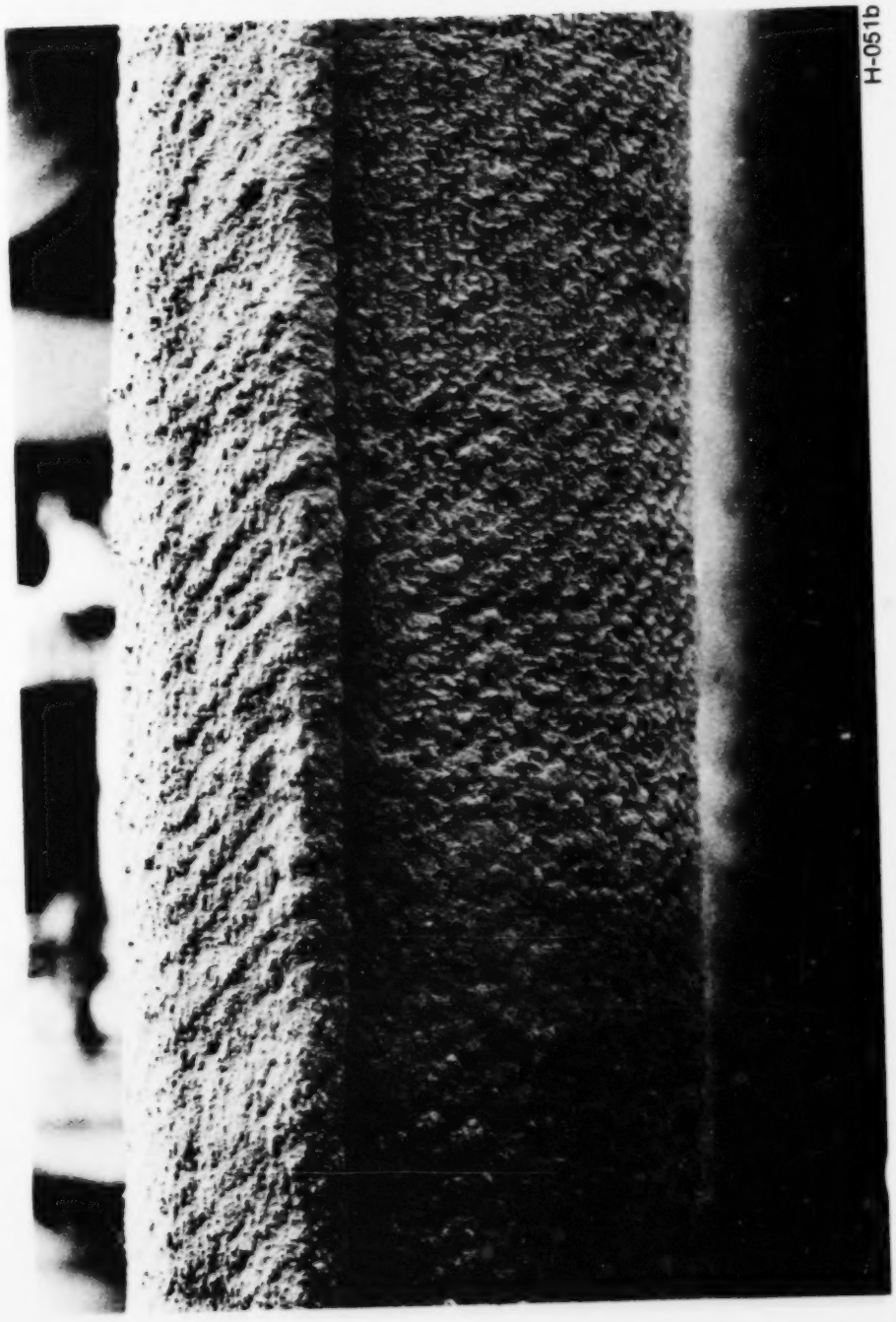

Figure 24. Woven Fiberfrax -- post-test dust cake.

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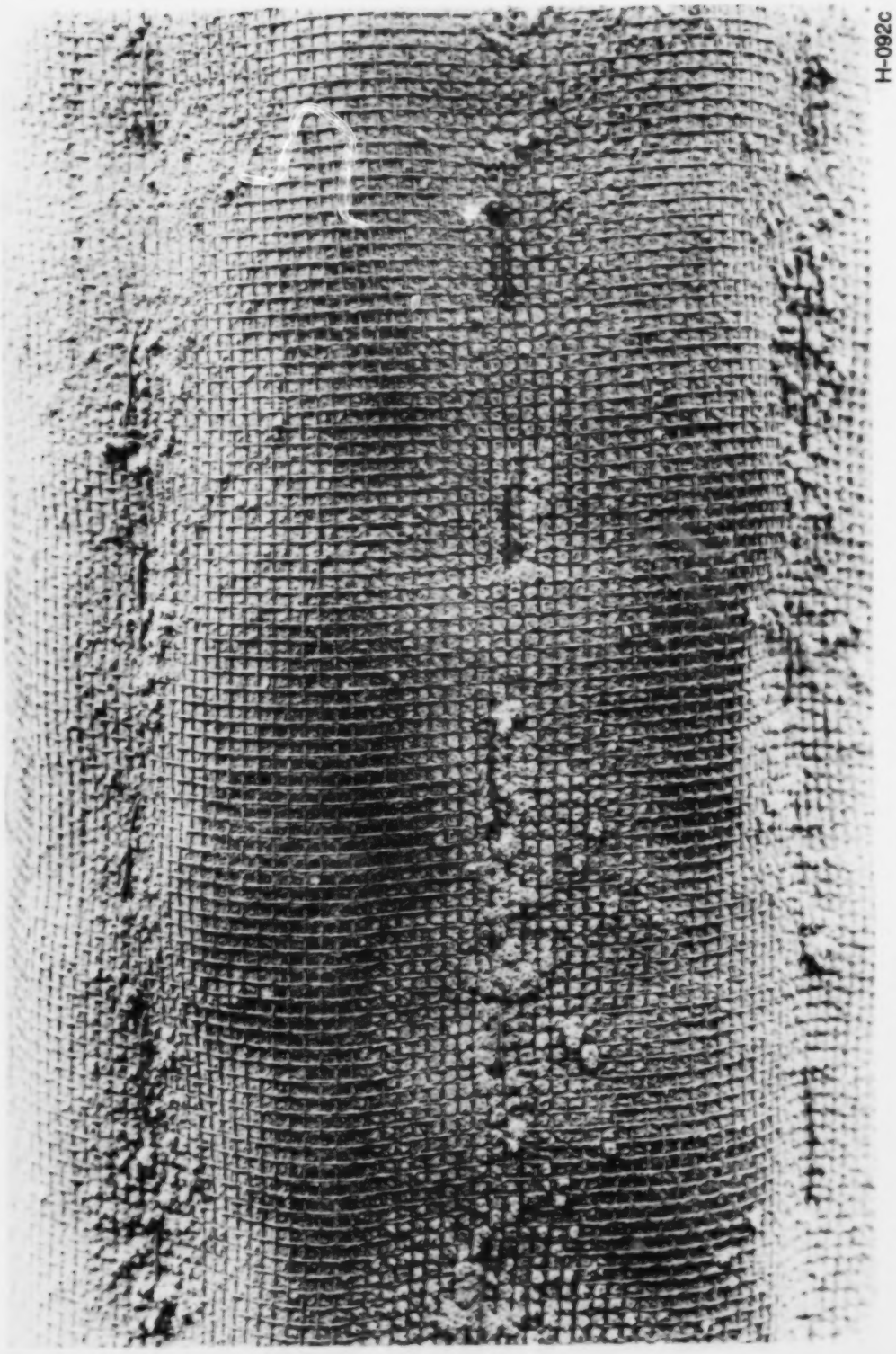

Figure 25. Fiberfrax blanket -- post-test dust cake.

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(0.0024 gr/$_a$ft^3). Figure 25 shows that the dust was concentrated near the places where wire penetrated the filter element. This concentration of dust near the wire penetration points could also be seen on the inside of the element. Thus, most of the dust which penetrated apparently did so through the holes made by the wires. It is reasonable to expect that a filter element without holes will experience less penetration; additionally less frequent cleaning pulse interval will reduce penetration.

Filter Performance Tests

Filter performance tests were intended to simulate actual filter operation at high temperature and pressure for a period of 200 hours. The filter media configuration which we have selected as most promising consists of an approximately 1 cm thick layer of saffil alumina blanket insulation material. This ceramic material is contained between two layers of knit 304 stainless steel screen. The first 200 hour test was performed at a nominal air-to-cloth ratio of 5 to 1 (2.54 cm/sec). Pulse duration was 150 ms. Pulse internal was one cleaning cycle every 10 minutes. Pulse pressure was 1100 kPa. Cleaning was performed "off-line" with 4 second bleed-down followed by reverse flow for 2 seconds, the pulse super-imposed followed by a 2 second settling period prior to continuing the filtration cycle.

Exxon miniplant flyash was used as the test dust. A fine dust D_{50} = 4 μM was used for the first 75 hours. When this dust was no longer available, a course sample D_{50} = 19 μM was used for the remainder of the test.

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Cumulative dust fed, total dust collected downstream and overall collection efficiency by mass are plotted as function of time on Figure 26. Note that inlet concentration was high (an overall average of 14.4 g/Nm^3). Shortly after the fine dust was substituted with the coarse, overall efficiency was reduced and the rate of penetration in weight per unit time was increased. Later, at about 120 hours and again at 150 hours, the rate of dust feeding was reduced. The rate of penetration seemed to follow this. These occurrences are consistent with leakage through a defect mechanism in the media. Visual examination of the inside surface of media after the test revealed it to be substantially clean with some localized staining. Overall collection efficiency remained high throughout the test never falling below 99.965 percent. Outlet concentration as a function of time is shown on Figure 27. These results are consistent on a mass basis with turbine requirements as reported by Sverdrup in EPA 600/9-78-004. Dust collected downstream was in the form of large flake agglomerates, some of which resembled rust scale. These are probably artifacts of the test and test set-up -- cooling and condensation. However, they make if difficult or impossible to obtain fractional efficiency for this run. The outlet concentrations reported above are based on a flow of 0.566 Nm^3 per minute during the time that dust was being fed (200 hours). They do not include the additional flow which occurred during warm-up and cool-down when the dust feeder was off. Because of various difficulties occurring with the test rig, the run was interrupted many times. Pressure drop was maintained at less than about 0.75 kPa (3 in H_2O) over the entire test.

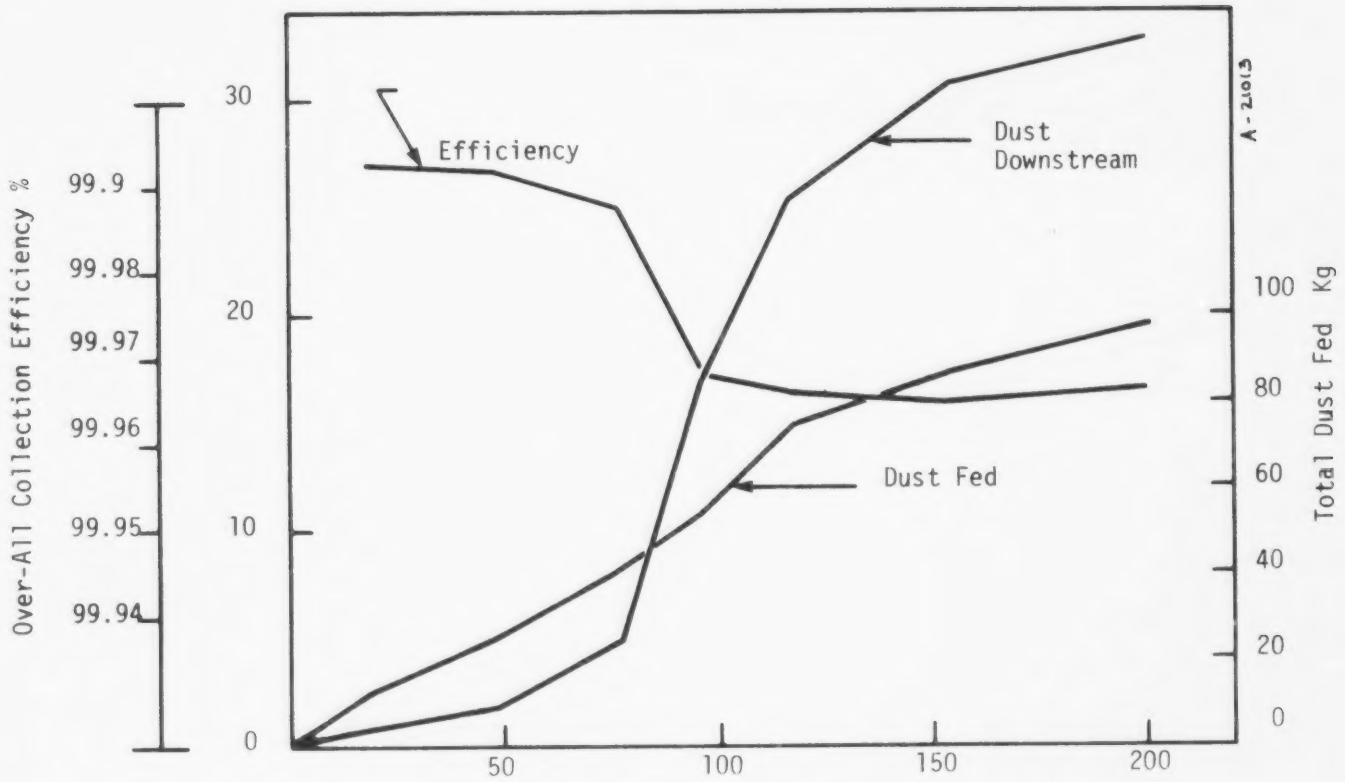

Figure 26. Filter characteristics 2.5 cm/sec.

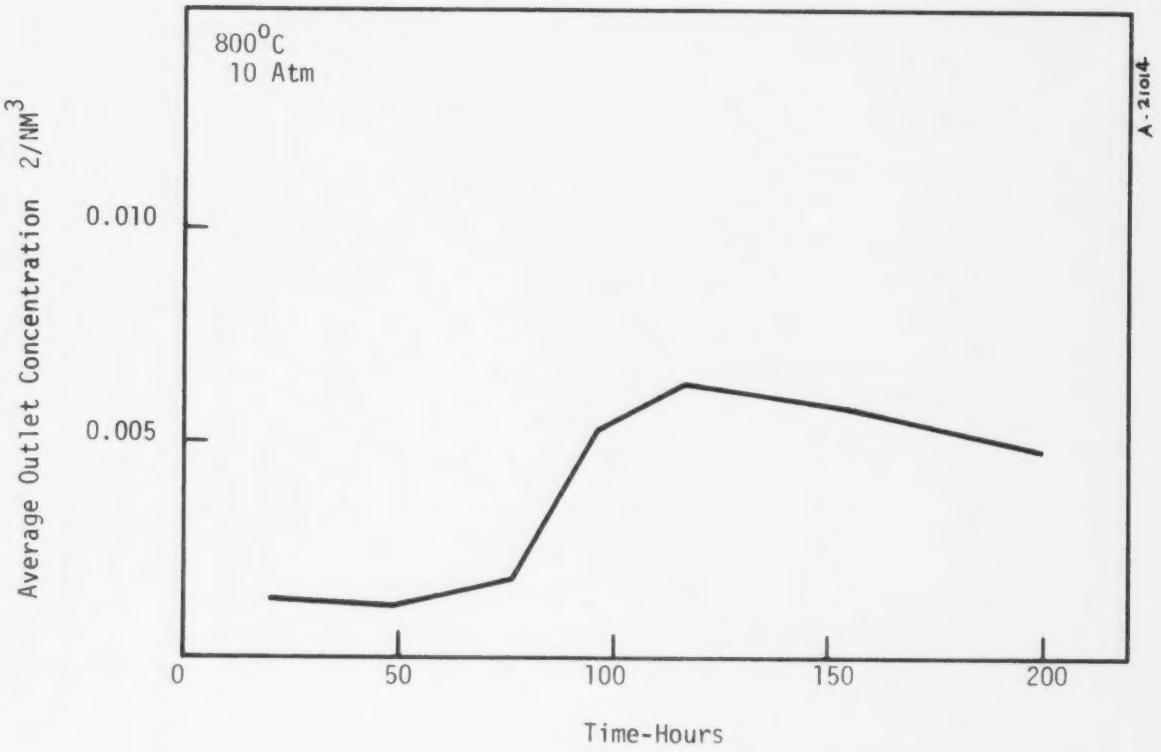

Figure 27. Outlet concentration 2.5 cm/sec.

For the second 200-hour test we attempted to achieve the highest air-to-cloth ratio possible with the present test rig configuration. This test was performed at an air-to-cloth ratio of 18 or 9 cm/sec face velocity. Filter face velocity was only 8.4 cm/sec for the first 11 hours. The increase to 9 cm/sec was accomplished by operating two flow limiting orifices in parallel. Because of compressor limitations, it was only possible to maintain a system pressure of 500 kPa. Earlier tests were run at system pressures of 930 kPa. Cleaning pulse pressure was set at 860 kPa to compensate for the reduced system pressure. Cleaning cycle, pulse duration and pulse interval were the same as in the previous test at 2.5 cm/sec with both tests using offline cleaning.

Flyash from the Exxon Miniplant was used as the test dust. This dust had a D_{50} = 19 μm. Cumulative dust fed, total dust collected downstream and over-all collection efficiency by mass are plotted as a function of time in Figure 28. Outlet concentration as a function of time is shown in Figure 29. Cleaned-down pressure drop was maintained at less than 1.25 kPa (5 in H_2O) throughout the test.

This data indicates that performance at high airflow velocity was even better than that achieved in the previous test. The test filter element was able to maintain high efficiency performance for the entire period of the test. Thus, evidence is now available that indicates turbines can be protected from particulates using ceramic fiber filters operated at filter face velocity at least as high as 9 cm/sec.

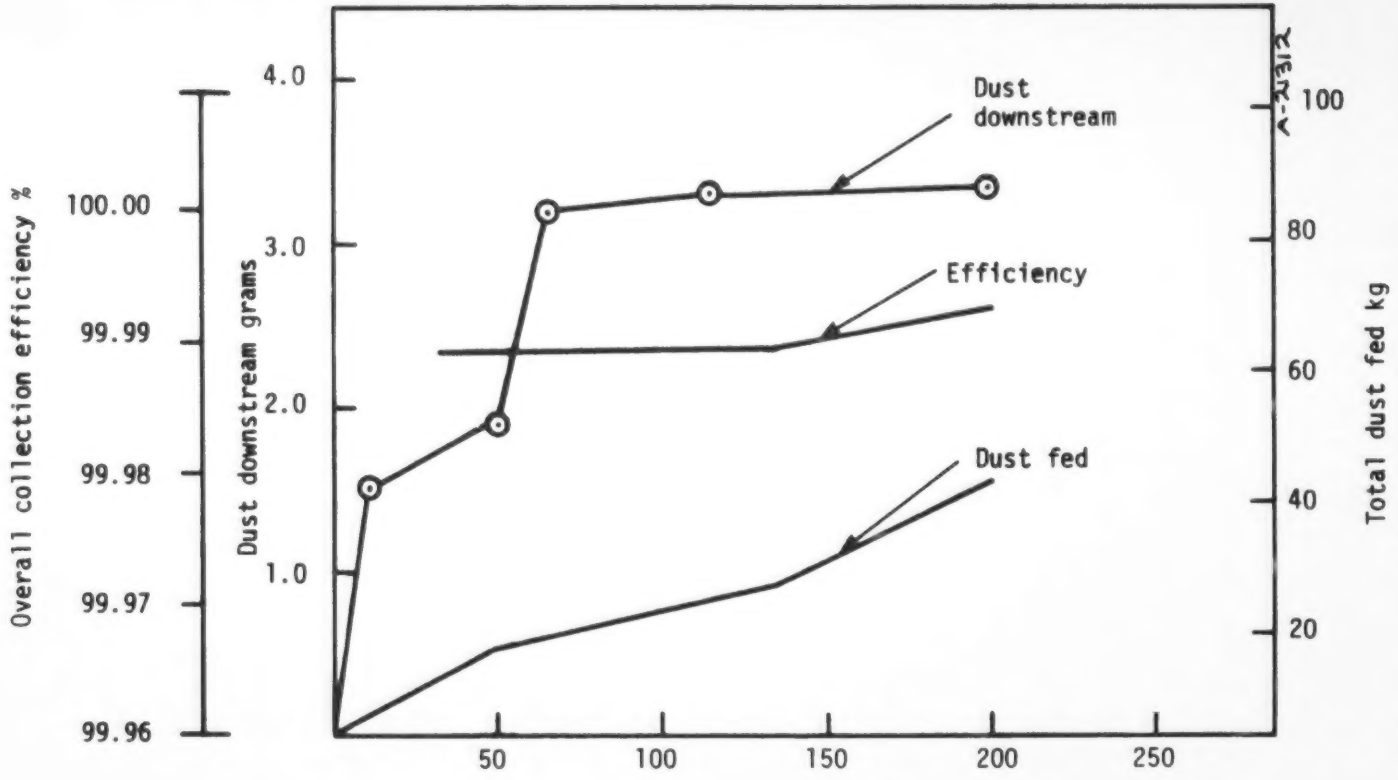

Figure 28. Filter characteristics 9cm/sec.

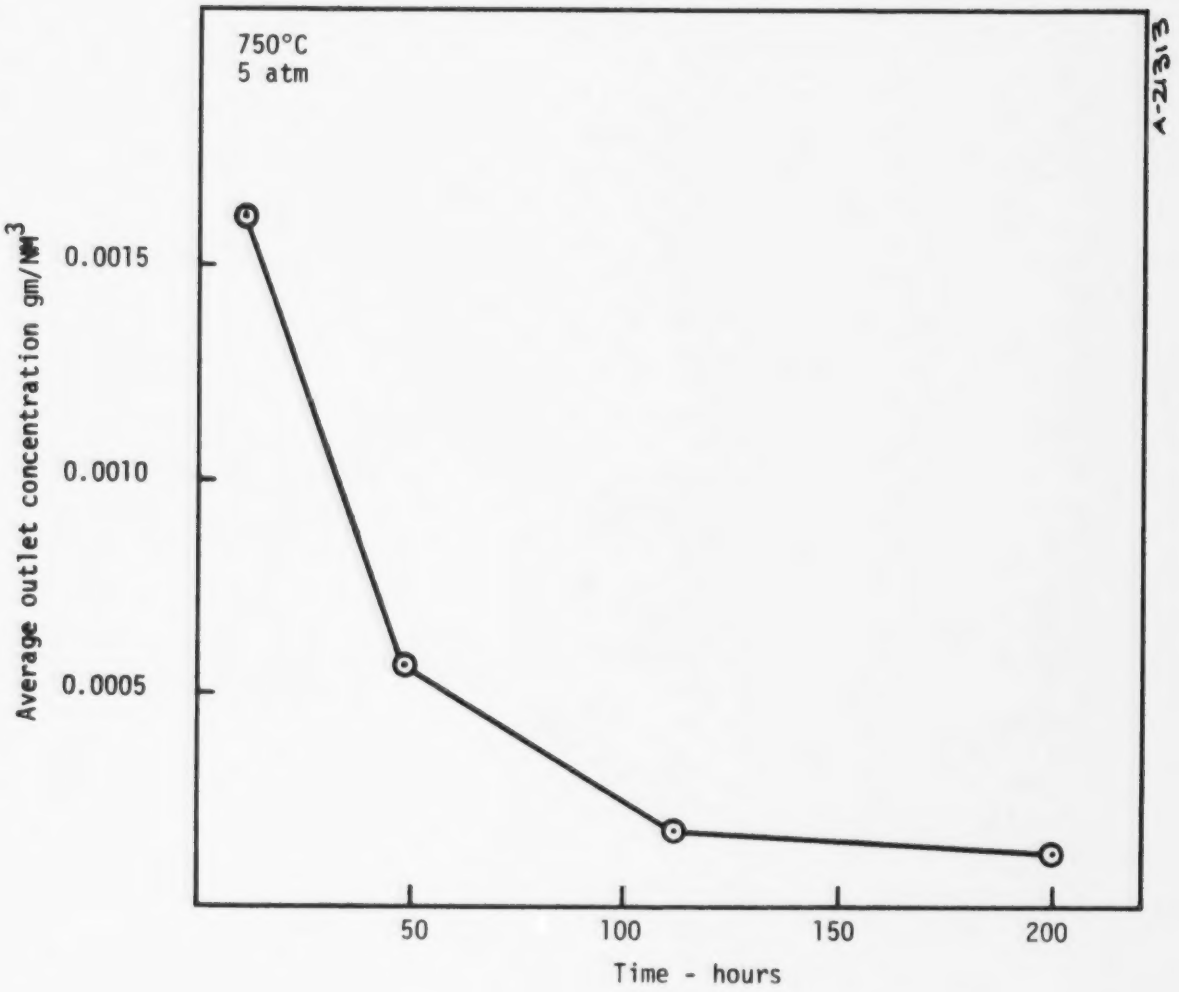

Figure 29. Outlet concentration 9 cm/sec.

APPENDIX A

Following is a list of media samples. The list contains descriptive information taken from advertising literature for each material. In examining these data, the reader should remember that in general these materials were not produced for filtration applications. Based on this information none of the materials can be recommended or rejected. Additional information will be required before the judgment can be made. The available information does indicate that at least some of the materials will probably offer good filtration performance.

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LIST OF SYMBOLS

d_p = Particle diameter

d_f = Fiber diameter

C' = Cunningham correction factor

ρ_p = Particle density

U_g = Gas velocity at media face (flow/area)

μ_g = gas viscosity

k = Boltzmann constant

T = Absolute temperature

DOP Test Results, High Temperature Filter Media

Media Samples — Description

Astroquarts (J. P. Stevens)	Cloth (with binder)	
	Style 570:	5 Harness Satin 300-2/8, 27 mils thick, 19.5 oz/sq. yd., 38 x 24 thread count/inch, 325 (warp) and 300 (fill) pounds/inch width breaking strength. Pure Silica (99.9%), 2000°F service temperature. Filament diameter ~ 6 microns)
	Style 581:	8 Harness Satin 300-2/2, 11 mils thick, 8.4 oz/sq. yd., 57 x 54 thread count/inch, 175 (warp) and 170 (fill) pounds/inch width breaking strength. Pure Silica (99.9%). Good to 2000°F continuous service. ~ 6 micron filaments
	Custom Weave: FMI Astroquartz	Crow foot Satin 300-2/2 (warp), 4/2 (fill) 54 (warp) x 36 (fill) threadcount per inch, ~ 12 mils thick, ~ 11 oz/sq. yd. Pure Silica (99.9%), good to 2000°F service.
Refrasil (Hiteco)	(Fibers 8 to 10 microns diameter)	
	Irish (Chromized) C 1554-48:	8 Harness Satin, 26 mils thick, 19.2 oz/sq. yd., 53 x 40 thread count per inch, 96 (warp) and 62 (fill) pounds/inch breaking strength. Consists of almost pure Silica with 1 to 3% Chrome Oxide. Continuous use to 2300°F.
Refrasil	Heat Cleaned (Preshrunk)	
	C 100-48:	8 Harness Satin, 26 mils thick, 18.6 oz/sq. yd., 52 x 39 thread count per inch, 86 (warp) and 61 (fill) pounds/inch breaking strength. Consists of almost pure Silica (99%+). Good to 2300°F.
	C 100-96:	12 Harness Satin, 50 mils thick, 37.1 oz/sq. yd., 50 x 39 thread count per inch, 130 (warp) and 65 (fill) pounds per inch breaking strength. Essentially pure (99%+) Silica. Good to 2300°F

Media Samples — Description (Continued)

Fiberfrax Cloth	No organic binder (removed), 2300°F service temperature	
	L-126TT grade:	1/8" thick, twill weave, 21 pcf, 32 oz/sq. yd.
	L-144TT grade:	1/10" thick, twill weave, 28 pcf, 34 oz/sq. yd., has nichrome wire insert, strong to 2000°F
Fiberfrax Paper	52% Al_2O_3, 48% SiO_2, 2300°F service temperature, up to 1" long, 2-3 microns (mean) fibers, 2.53 gm/cc density	
	970-AH grade:	1/32" thick, no binder, 12 pcf, 4.5 oz/sq. yd.
	970-J grade:	1/8" thick, has up to 5% binder, 10 pcf, 15 oz/sq. yd.
Zircar Zirconia	Felt ZYF-100:	19 oz/sq. yd., 0.1" thick, 15 pcf, 96% voids, 600 scfm/ft^2 at 0.5 psi, 5.8 gm/cc density, 4.5 μm fibers, no binders. Breaking strength 1.6 pounds/in. width
Saffil Alumina (1C1)	Fiber density 3.4 gm/cm^3, 3000°F service temperature, 3 micron fibers, 1-2" long, 1.5 cm^2/gm surface area, 95% Al_2O_3 — 5% SiO_2	
	Mat	4 pcf, ½ in. thick, 2.4 oz/sq. yd., no binder
	Paper	12 pcf, 0.04 in. thick, 6 oz/sq. yd., has binder
Kaowool (Babcock & Wilcox)	47% alumina — 53% silica, good to 2600°F, 2.8 micron fibers, 2 in. long and up to 4 in. long. Has no binder. 2.6 g/cc density, 6 pcf, ¼, ½, and 1" thick, 18, 36, 72 oz/sq. yd.	
Fiberfrax (Carborundum)		
	Durablanket	48% Al_2O_3, 52% SiO_2, 2300°F service temperature, long fibers, 2-3 micron (mean) fiber diameter, density 2.62 gm/cc. No binder, 6 pcf, ¼ in., 18 oz/sq. yd.
Fiberchrome (J. Manville)	Felt	41% alumina, 55% silica, 4% Cr_2O_3. good to 2700°F. 3.5 micron fibers, 8 pcf, ½ in. thick, 48 oz/sq. yd.

Media Samples — Description (Concluded)

Refrasil (continued)		
	UC 100-48:	8 Harness Satin, 26 mils thick, 18 oz/sq. yd., 46 x 36 thread count per inch, 80 (warp) and 60 (fill) pounds per inch breaking strength, good to 2300°F. 99%+ Silica
AB-312 (3M Co.)		Heat Cleaned. Alumina-Boria-Silica, 390 filament strand, 11 micron diameter filaments, 250,000 psi tensile strength, 22 x 10^6 psi modulus, 2300°F service temperature, 2.5 gm/cc density
	Style 22B:	50-1/0, 32 x 38 thread count/inch, 9.3 oz/sq. yd, 12 mils thick basket weave.
	Style 22T:	50-1/0, 32 x 25 thread count/inch, 7.6 oz/sq. yd., 10 mils thick, twill weave
Zircar Cloth (Zircar Corp)	ZYW 30A:	20 oz/sq. yd., 0.030 in. thick, 5 Harness Satin, 63 pcf, 83% porosity, 5.7 gm/cc density, 5 micron continuous filaments. Breaking strength 4 pounds/in. width BET surface area 1 m^2/gm, 92% Zr_2O_3 - 8% Y_2O_3. Good to 3300°F, 2-ply x 480 filament yarn, 45 x 34 threads/in.